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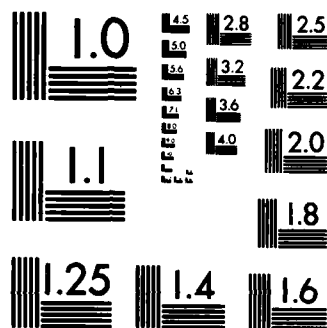
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Measurements Of Distributed Combustion

by P.C. Braithwaite and
M.W. Beckstead

September 1984

Prepared for
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by
Brigham Young University
Department of Chemical Engineering
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by Al is greater than that caused by ZrC. Because the reaction of Al releases more than twice the energy ZrC does, it would be expected to have a greater influence on the system than ZrC. The increase in the acoustic growth rate is the result of energy being added to the system by the distributed combustion of the particles. The increase in the acoustic growth rate due to distributed combustion was found to be directly related to the heat of reaction.

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CHAPTER I

INTRODUCTION

The problem of combustion instability in solid rocket propellants has been studied extensively over the past three decades. At times unstable burning in a rocket motor is a minor nuisance and at other times its results can be catastrophic. During the course of this research much has been learned and many tools have been developed to help the scientist understand the phenomena associated with unstable combustion. However the problem is very complex and many of its underlying causes are not clearly understood. As a result the techniques used to prevent or control combustion instability often lack a firm theoretical basis.

Acoustic Suppressants

The most common way oscillatory combustion is controlled in rocket motors today is through the use of additives known as acoustic suppressants. The perfect suppressant would control each of the oscillatory modes of a motor. Unfortunately suppressants that work well at one frequency, such as that produced in a longitudinal mode, can be quite ineffective at other frequencies, such as those produced by tangential mode oscillations. Still some suppressants have been relatively successful in suppressing oscillations in operational motors. The more successful suppressants include aluminum (Al), zirconium carbide (ZrC), and graphite.

While effective suppressants have been found for certain applications, the basis for choosing the type, size, and concentration of suppressant particle is not well founded. Suppressants apparently work by one or more of three mechanisms: 1) energy loss resulting from viscous dissipation due to drag forces; 2) modification of the propellant combustion response function or

3) energy interchange due to distributed combustion.

Viscous dissipation of acoustic energy by drag forces on a suspended particle is the most commonly recognized mechanism, being a direct analogy to suspended moisture in fog. The combustion of aluminum in solid propellant not only releases a large amount of energy, but it produces a dense smoke in the form of aluminum oxide droplets (approximately 1-2 micron diameter). The small aluminum oxide particles are often very effective in damping out unwanted acoustic oscillations through viscous dissipation. A second mechanism, whereby an additive can effect acoustics occurs at the burning boundary of the system. Solid additives within the propellant can have a catalytic influence on the propellant combustion, modifying the combustion response. The best known example of this is probably aluminum oxide. Not only does aluminum oxide provide the viscous drag dissipation previously discussed, but it is also a weak combustion catalyst in composite propellants. An additive that influences the steady burning of a propellant can also be expected to influence the transient response of the propellant. The change in transient response can produce either a more stable acoustic environment or a more unstable environment. The third mechanism considered is due to the effect of a particle burning as it traverses a relatively large portion of the system. As it does so, the interchange of energy between the burning particle and the acoustic environment can result in either a driving or damping contribution to the acoustics of the system. This third mechanism is the primary area of study at the present time.

The Rijke Burner

The complex environment inside a burning rocket motor is a very difficult (and expensive) place to study acoustic suppressants. As a result different devices have been used to simulate the acoustic environment created inside a

rocket. These devices have usually been some adaptation of a T-burner. For the current study, a Rijke burner has been developed, for a more detailed description refer to Gordon (1984). The Rijke burner, see Figure 1, or singing flame is a gas burner with a cylindrical body and a flameholder, usually a wire screen, placed in the lower half of the tube. As the gases burn, acoustic oscillations (usually of the longitudinal mode) similar to those produced by an organ pipe are generated. The first correct explanation to the origin of the combustion driven oscillations present in a Rijke tube (the Rijke tube differs from the Rijke burner only in that the Rijke tube utilizes natural convection while the Rijke burner utilizes a flame-fed forced convection) was postulated by Rayleigh (1878) who stated:

"If heat be given to the air at the moment of greatest condensation, or taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged."

In other words for the oscillations to be sustained heat must be added to the gas at the moment of greatest compression or taken away at the point of greatest expansion.

For the past two decades the T-burner has been one of the standard tools used to evaluate the stability of a given propellant formulation. Although the T-burner has been more widely used to study acoustic suppressants than the Rijke burner, there are several advantages to using a Rijke burner. First, because the Rijke burner does not use solid propellant, an additive can be tested independent of the propellant burning, allowing a separation of mechanisms between the modification of the burning surface response and effects of distributed combustion. Second, the system can easily be tested with or without particles, easily evaluating system effects. Third, a high pressure environment is required to burn solid rocket propellant efficiently

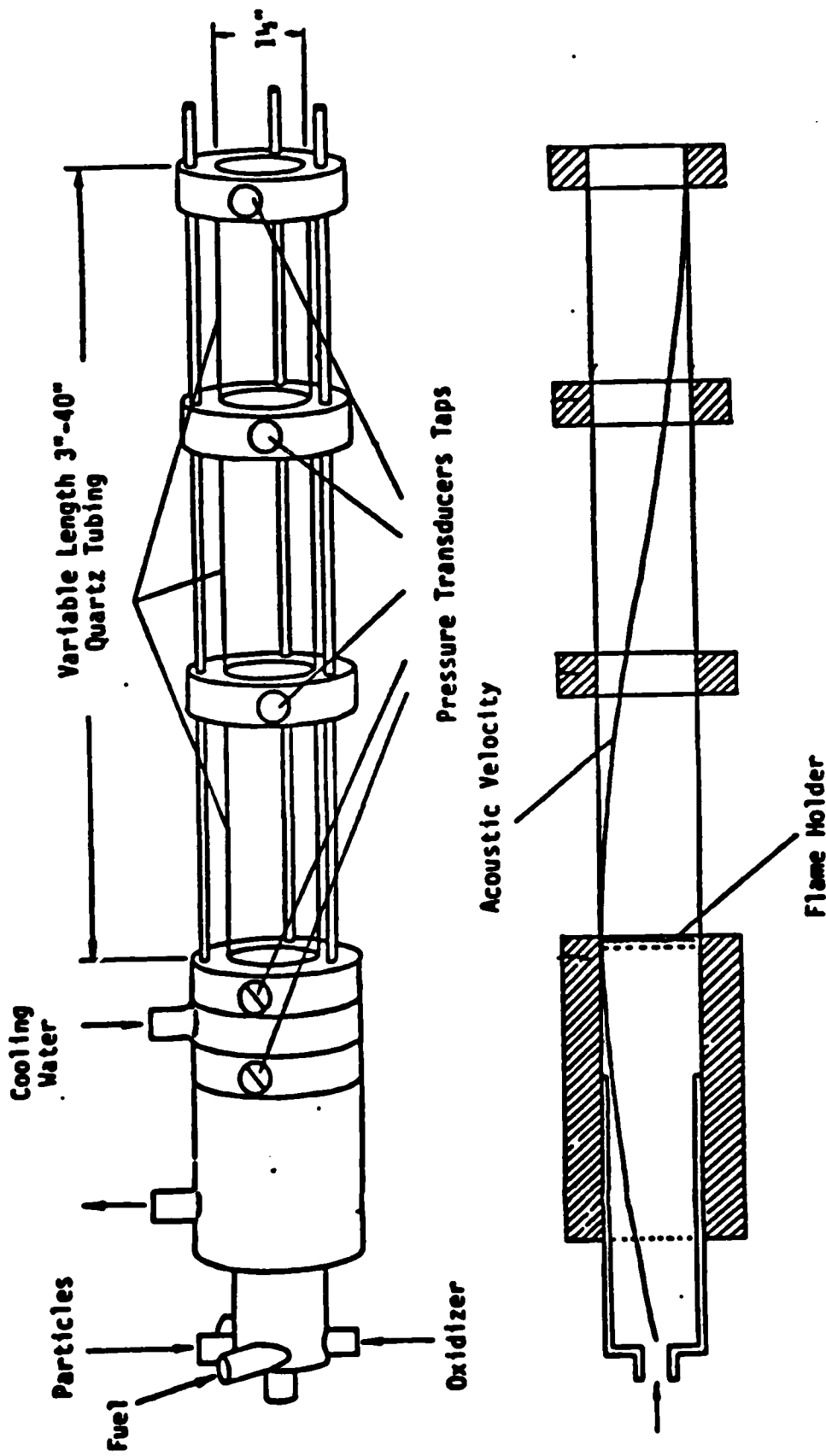


Figure 1. Sketch of Rijke tube burner used in Thesis project.

while the Rijke burner can operate at atmospheric pressure. This makes it easier to observe the behavior of an additive in the Rijke burner as well as reducing operating costs significantly. And finally, various types of particles (reactive or inert) can be tested under identical conditions to better identify actual mechanistic action.

The purpose of the research described in this thesis is to develop and refine a method for testing and evaluating acoustic suppressants utilizing the Rijke burner. The balance of this document is organized as follows: chapter II contains a survey of research applicable to this problem. A description of the experimental development is found in chapter III. Chapter IV contains the results obtained with a discussion of their significance and limitations, and the conclusions which can be drawn from these results are found in chapter V.

CHAPTER II

BACKGROUND

One of the most common techniques used to deal with oscillatory combustion in solid propellant rocket motors today is simply to add an acoustic suppressant to the propellant mixture. While this technique is often successful, only a limited amount of research has been performed to learn how and why acoustic suppressants work. In addition to reviewing the research which has been performed on acoustic suppressants this chapter also gives a brief review of some of the techniques used to analyze combustion instability.

Method of Data Reduction

The rate at which acoustic oscillations grow is one of the important items used to characterize acoustic instability. To calculate the acoustic growth rate (Culick, 1974), it is necessary to determine the average frequency and the amplitude of each cycle during the period of growth from a record similar to the one shown in Figure 2.

The acoustic growth constant may be defined as

$$P_0 = P_n \exp(\alpha t_n) \quad (1)$$

where P_0 is the amplitude of the first cycle, P_n is the amplitude of the n^{th} cycle and t_n is the time interval between P_0 and P_n . If the growth rate is linear then a plot of $\ln(P_n)$ versus time (or cycle number) will be a straight line with a slope α . In other words the growth constant will be given by

$$\alpha = \ln(P_n/P_0)/t_n \quad (2)$$

In many cases the growth rate is non-linear and the simple relationship between α and pressure given in Equation 2 is not valid. Methods are not

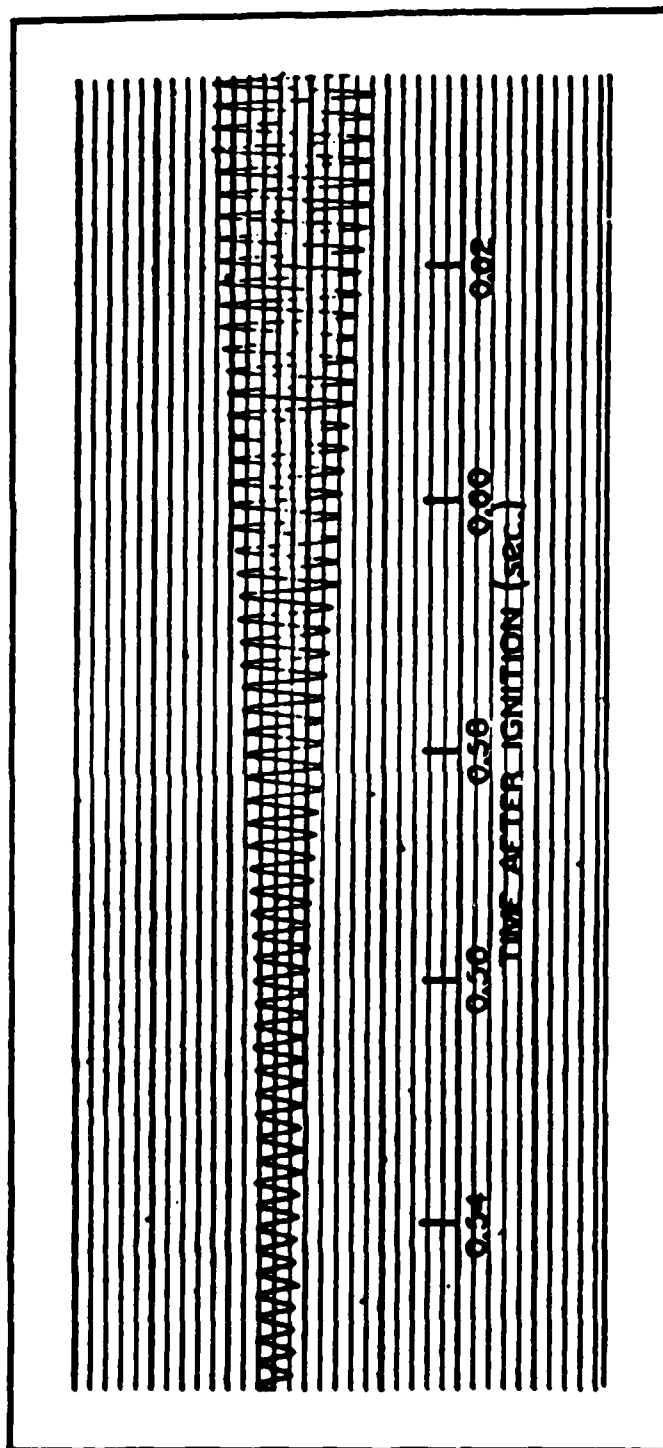


Figure 2. Typical period of growth of an unstable pressure oscillation (in a variable area T-burner); (from Culick, 1974).

available for treating non-linear growth rates, however studies have been performed dealing with this problem (e.g. Culick, 1971 and Levine, 1974) but are beyond the scope of this work and will not be reviewed here.

Particle Damping

As stated earlier acoustic suppressants apparently work by one or more of three mechanisms. Energy loss due to viscous damping (i.e. particle damping) is the most well accepted and understood of these three mechanisms. The theory of particle damping which includes the viscous and elastic damping provided by non-reactive particles was developed by Epstein and Carhart in 1953. In their theory the amount of acoustic damping provided by particles suspended in a gas was found to be a primary function of the frequency of the oscillations, particle concentration, and particle diameter. Experimental studies by several investigators have supported the validity of this theory, e.g. Zink and Delsasso (1958), Dobbins and Temkin, (1964) and Temkin and Dobbins, (1966).

The equations arrived at by Epstein and Carhart were simplified by Temkin and Dobbins (Aug. 1966), although the basic theory was not altered. The work of Temkin and Dobbins was modified slightly by Culick (1974) who arrived at the following equation:

$$\alpha_D = -1/2 \frac{C_m}{(1 + C_m)} \sum_i \left(\frac{\omega^2 \tau_i}{1 + \omega^2 \tau_i} \right) X_i \quad (3)$$

where α is the acoustic damping coefficient in sec^{-1} , ω is the angular frequency, C_m is the mass fraction of particulate matter, X_i is the mass fraction of particulate matter with diameter i , and τ_i is the viscous relaxation time, $\rho D_i^2 / 18\mu$, for particles of diameter i . This equation shows that the damping provided by a given particle is primarily dependent on the particle diameter and the frequency of oscillation; however it is also a

function of the particle concentration, particle density and the viscosity of the gas.

Acoustic Suppressants in Reactive Environments

It is convenient and practical to study the effect of particle damping in a non-reactive environment. However, the effect of distributed combustion must be studied under reactive conditions. Unfortunately the amount of research undertaken to study acoustic suppressants in a reactive environment has been relatively limited. Those who have done so, have generally used T-burners or small scale rocket motors, to simulate the acoustic environment of a full scale rocket motor. If propellants containing reactive acoustic suppressants (e.g. aluminum, zirconium carbide) are used in small rocket motors or T-burners all three mechanisms (particle damping, catalytic effects, and distributed combustion) may be present. When the Rijke burner is used to study the same acoustic suppressants, the catalytic effect a given additive may have on burning solid propellant is eliminated, however it is possible that the additive will catalyze the gas flame of the Rijke burner.

T-Burners Studies

Studies were performed by workers at the Naval Weapons Center (Derr et al. (1975) and Kraeutle et al. (1976)) using T-burners which demonstrated the validity of the particle damping theory of Temkin (1966) as later modified by Culick (1974). In the work reported by Derr (1975) two different types of propellant were used, one containing 5% aluminum oxide and the other containing 10% aluminum oxide (all other ingredients were identical). In each case the particle size distribution of aluminum oxide was identical. Each of the propellants were tested at three different frequencies 280, 700, and 1800 Hz. During the tests the damping provided by each propellant was

measured. Also, after burning the propellant they collected the particles and performed a particle size analysis. Once the particle size distribution was known the theoretical damping was calculated using Eq. 3. Agreement between the experimental results and predictions using theory was good.

Kraeutle et al. (1976) extended the work by varying the particle size distribution while holding the amount of aluminum oxide in each propellant constant. The mean diameter of the aluminum oxide used was 6.8 micron and 14.8 micron. Theoretically, these two sizes should provide different damping characteristics. Unfortunately after combustion of the propellant the smaller particles seemed to agglomerate more than the larger particles so the actual difference in damping was reduced. However agreement between the calculated damping based on the agglomerated particle sizes and measured damping was excellent, further substantiating the validity of the particle damping theory. The results obtained by Derr (1975) and Kraeutle (1976) are summarized in Figure 3.

Small Rocket Motors

Perhaps the most comprehensive study of acoustic suppressants was performed by Rudy (1981). He systematically tested many of the popular acoustic suppressants in use today, as well as many other seldom used suppressants, in two small scale motors which exhibited tangential mode oscillations in the frequency range of 12 to 23 kHz. An additive was judged to be effective if it prevented a DC pressure shift in the small test motors. He also looked at window bomb movies and ranked the propellants relative to the ignition location of the additive. The results of his study are summarized in Table 1. While the tests Rudy used to determine the effectiveness of a given additive do yield important information they are very qualitative in nature. However, his results are significant as they show

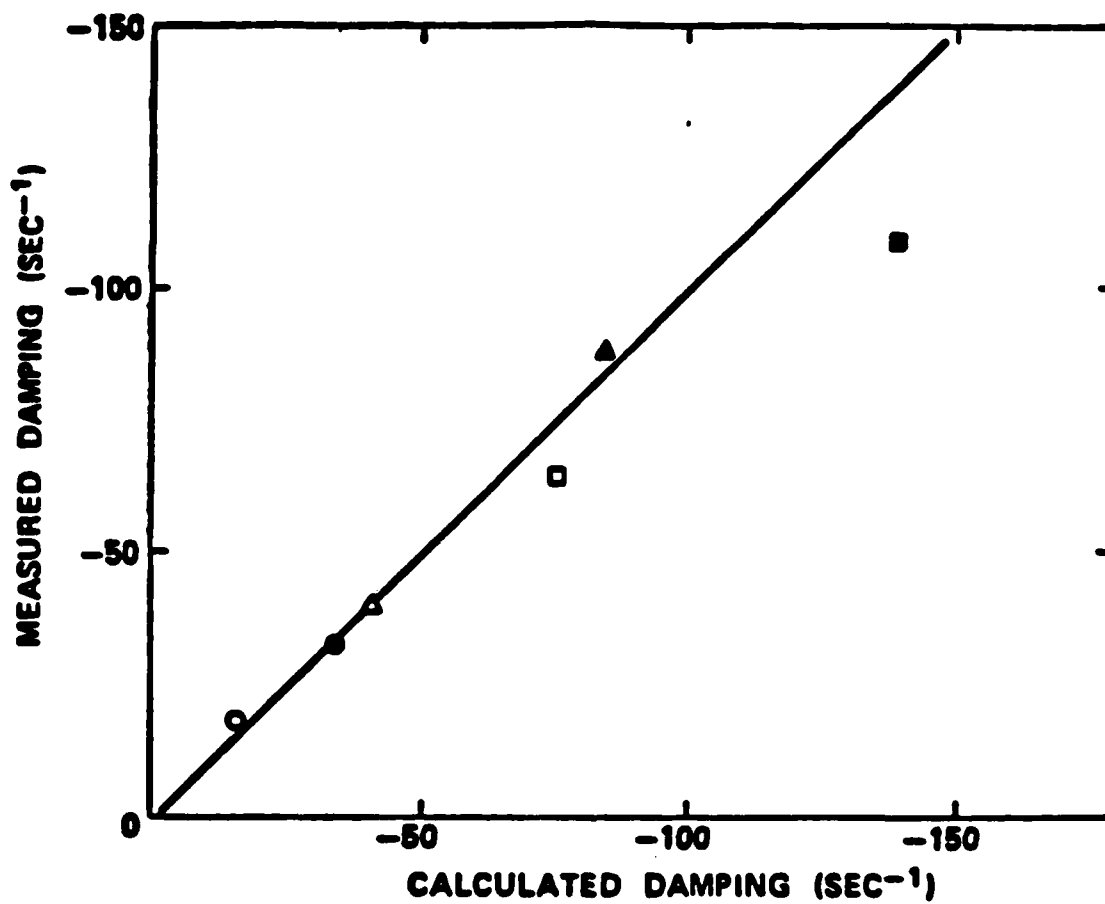


Figure 3. . Comparison of measured with calculated damping rates for propellants containing 5% (\circ, Δ, \square) and 10% ($\bullet, \blacktriangle, \blacksquare$), aluminum oxide. Measurements were made at approximately 280 Hz (\circ, \bullet), 700 Hz (Δ, \blacktriangle) and 1800 Hz (\square, \blacksquare); (from Kraeutle, 1976).

Table 1

Summary of study performed by Rudy (1981) to characterize combustion stabilizers; (from Rudy, 1981).

Effectiveness in 23-kHz and 15-kHz Burner Tests	Candidate Stabilizer	Incandescent Particles		
		Population at Propellant Surface	Location of First Appearance	Population Above Propellant Surface
High	Aluminum, 5 μ m	Dense	On surface	Dense
High	Zirconium, 2 μ m	Very dense	On surface	Very dense
High	Silicon carbide, 3 μ m	Very dense	On surface	Very dense
High	Zirconium carbide, 3 μ m	Very dense	On surface	Dense
Moderate	Aluminum, 30 μ m	Moderate	On surface	Moderate
Low	Zirconium oxide, 4 μ m	None	--	Sparse
None	Misch metal, <44 μ m	None	>0.75 cm above surface	Dense
None	Silicon dioxide, 2 μ m	None	>0.5 cm above surface	Sparse
None	Tungsten carbide, 8 μ m	None	--	None
None	Boron nitride, 1 μ m	None	--	None
None	None (baseline)	None	--	None

which additives work and which do not work in a high pressure and high frequency environment. In general (but not always) Rudy determined that smaller particles were more effective than larger particles. This was to be expected because of the very high frequency of his motors. Also, particles that would be expected to be reactive, such as aluminum or zirconium, were more effective than nonreactive particles, such as tungsten carbide or silicon dioxide. There was also a systematic trend showing that those additives that become incandescent at or near the surface are most effective.

Despite the extensive amount of information gathered by Rudy his conclusions are not well founded. Rudy concluded that the reason some additives were successful was due to a "pilot light effect," where the additive causes the propellant flames to ignite more readily than normal and thus avoid unstable combustion. However, if this were actually the case the steady state burning rate would also be expected to change due to the "pilot light effect" of the additive. In reality the additives were shown to have little effect on the steady state burn rate. Therefore, Rudy's pilot light mechanism does not seem consistent. Another conclusion arrived at by Rudy was that the theory of particle damping due to viscous drag was totally invalid. This is a very unrealistic conclusion considering the qualitative nature of his data and the extensive amount of quantitative data to the contrary. It is probable that many of the "ineffective" additives actually did provide some acoustic damping, just not enough to stabilize the motor.

Rijke Burner Studies

A comprehensive survey of literature dealing with Rijke burner has been performed by Gordon (1984) and Raun (1985). Of all the researchers who have studied the Rijke burner only Diederichsen (1963) has used it to study acoustic suppressants. The majority of his work was concerned with the

characterization of the burner without particles; however, he did test a small number of additives. Diederichsen ranked these additives in order of increasing damping effectiveness as follows: aluminum flake, atomized aluminum, titanium dioxide, magnesium oxide and asbestos powder, magnesium, aluminum oxide, and silica ('Microsil').

Unfortunately due to limitations within his experimental system he was only able to obtain qualitative results. Also no information about the relative sizes of the additives used is given which would have been very useful in evaluating the suppressants from a theoretical basis. Despite these shortcomings he did arrive at two significant conclusions: First, he concluded that the Rijke burner "sings by the same type of mechanism by which a rocket motor oscillates." Secondly, he concluded that the Rijke burner may be useful in the evaluation of acoustic suppressants.

CHAPTER III

EXPERIMENTAL DEVELOPMENT

This chapter briefly summarizes previous experimental developments and then describes the changes and improvements which have occurred most recently.

Summary of Test System

A block diagram of the basic experimental system is shown in Figure 4. The basic experimental system may be divided into three categories: first, the Rijke burner and oscillation control paddle; second, the particle feeding system which includes the particle feeder, precision balance, and strip chart recorder; and third, the instrumentation system which includes the transducer, amplifier, filter, galvanometers and oscillograph. The burner design and construction, establishment of a data acquisition system, initial work with particle feeding systems and initial oscillation control paddle design and construction were performed previously (Gordon, 1984). A brief description of the Rijke burner and the overall system is given below.

The Rijke burner used in this experiment, Figure 1, burns a mixture of propane, oxygen and nitrogen. It is water cooled, has an inside diameter of 1.45 inches and an adjustable lower section. Optical quality quartz tubes (1.45 inch i.d.) of varying length are placed on top of the burner and the flame is stabilized on a 20 mesh stainless steel screen. Gas flowrates to the burner are controlled with precision rotometers..

Initial work performed with particle feeders involved testing a screw type feeder and a fluidized bed feeder. Although that work was qualitative in nature, it did show that a fluidized bed type feeder was superior to a screw feeder for this application. A fluidized bed particle feeder which is suspended from an electronic balance is currently used to introduce particles

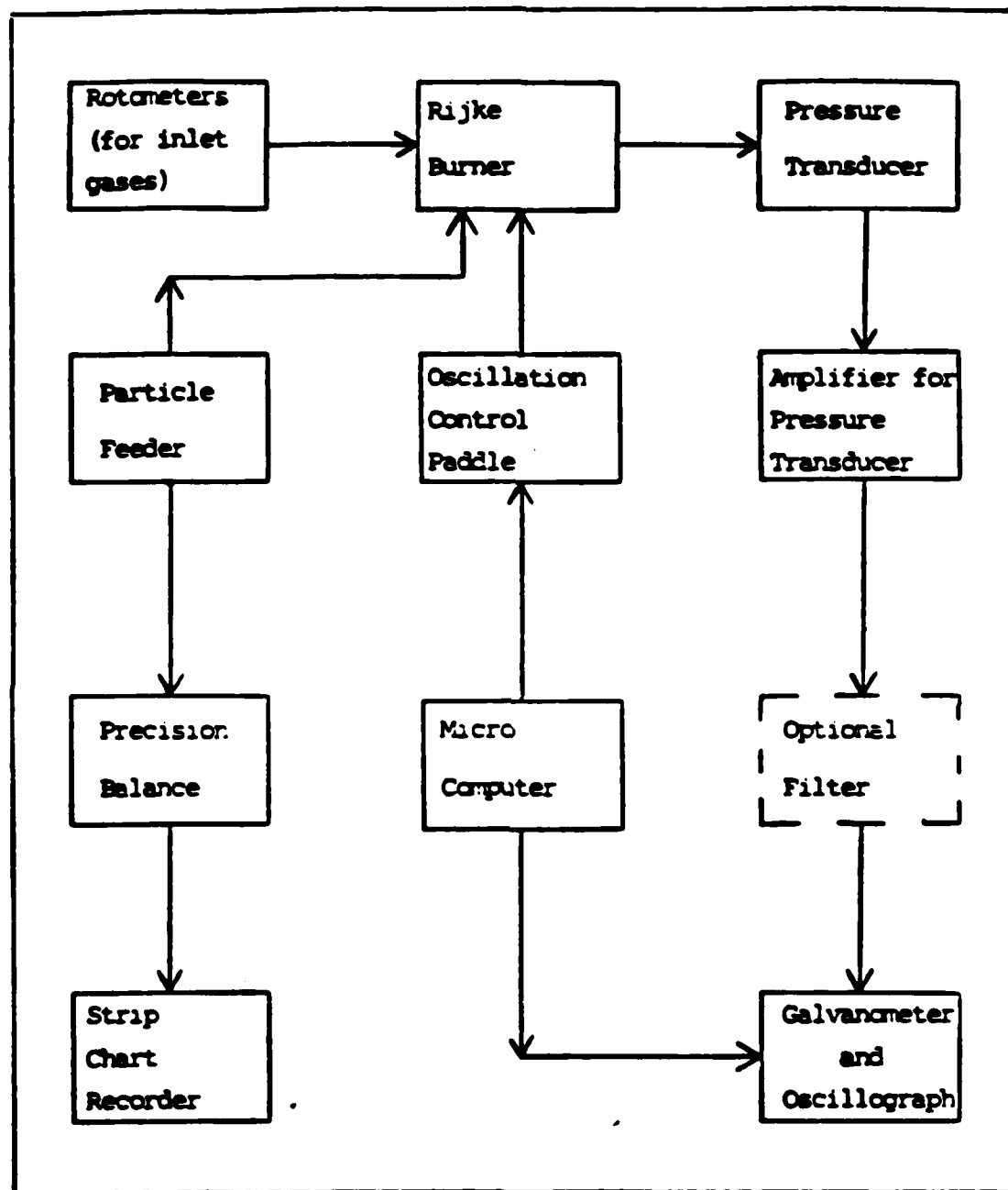


Figure 4. Block diagram of experimental system used to study acoustic suppressants.

into the burner, and will be discussed in detail later.

As the gases burn, acoustic oscillations of variable amplitude and frequency develop in the Rijke burner. To control the oscillations and obtain growth curves of these oscillations a paddle was developed which slides across the top of the quartz tube and shuts off the oscillations. It then moves back to its initial location allowing the oscillations to grow to their steady state value. The oscillations are monitored with high frequency pressure transducers, the transducer output is amplified and then recorded on a high speed oscillograph. To ensure the efficient collection of data both the paddle and oscillograph are controlled by a computer.

A computer program was written to control the paddle and visicorder. This program allows the operator to vary the number of times the paddle closes, the length of time in the open or closed position and turns the visicorder on and off. While the burner itself is still controlled manually (gas flowrates, ignition and etc.) through the use of computer control the process of data acquisition has become more uniform and efficient.

Paddle and Burner Stand

After some initial work with the system it became apparent that a new stand to hold the paddle and burner would be needed. There was a need to hold the paddle more securely so that when it moved back and forth to suppress the oscillations it would not produce unwanted vibrations. The vibrations produced by the paddle were transmitted through the system, picked up by the transducer and as a result distorted the signal recorded on the visicorder.

The new stand was designed to hold both the burner and paddle. However, even though the paddle was held more securely, and the magnitude of the vibrations was reduced, the extraneous vibrations persisted to a significant level. The new stand did not eliminate them completely as had been hoped.

Oscillation Control Paddle Refinement

As mentioned above one of the difficulties encountered in determining growth rates has been the elimination of extraneous noise due to the motion of the paddle. The paddle, Figure 5, is connected to a bi-directional air cylinder and is driven by high pressure air. When the paddle opens or closes, vibrations are produced which are transferred through the burner stand and the quartz tube, detected by the pressure transducer and then recorded. The paddle moves rapidly and has a significant amount of kinetic energy and momentum which must be absorbed without disturbing the system. When the paddle closes to shut down the oscillations the extraneous vibrations do not present a problem because the important information is contained in the growth curve not the decay curve. However, when the paddle is opened to allow the oscillations to grow, the vibrations produced by stopping the paddle are strong enough to disturb the transducer. At times the transducer signal due to the extraneous vibrations was added to the pressure oscillation signal in a constructive manner and other times it combined in a destructive manner. As a result the data were inconsistent.

To reduce these vibrations to an acceptable level, a shock absorbing system was developed using cork and three layers of surgical tubing. This helped reduce the magnitude of the vibrations while still allowing the paddle to shut down the oscillations when it moved to the closed position.

A second problem associated with the paddle was the fact that when the paddle was in the closed position the oscillations did not completely die out. Instead a lower frequency was produced which was characteristic of a closed-closed tube. This frequency appeared to be the fundamental mode, but it also contained higher harmonic frequencies. Because the oscillations did not completely die out when the paddle closed, when the paddle opened the

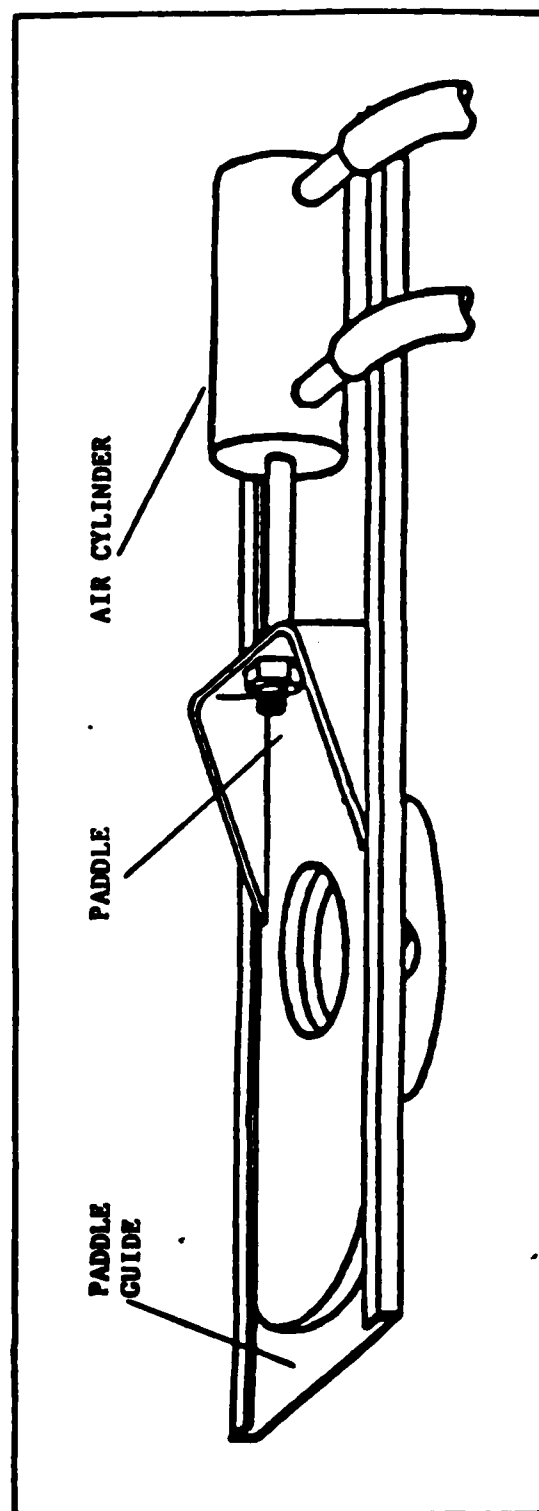


Figure 5. Diagram of paddle used to control acoustic oscillations in the Rijke tube.

oscillations did not start their growth from zero amplitude as desired. In an effort to keep these unwanted oscillations as low as possible the paddle was redesigned. The new paddle was similar to the original except that replaceable disks with several small holes drilled in it were used and a solid plate was mounted $3/32$ " above the holes, see Figure 6, so that the holes would be over the quartz tube when the paddle was in the closed position. This modification allowed gas to continue to flow out of the burner while still acting as a closed end to the pressure oscillations.

In theory, the small holes operate much the same way as ceiling tile does, they dampen sound waves. Different size holes absorb different frequencies better than others. As a first approximation the small holes were thought of as Helmholtz resonators, and using this assumption as a guide it was possible to estimate the proper hole diameter necessary to absorb certain frequencies. The actual amplitude of the unwanted oscillations can be controlled by varying the size and number of holes in the closed end of the paddle. Because the frequencies produced by the Rijke burner vary with burner length, oxygen to fuel ratio, nitrogen to oxygen ratio, etc., it was necessary to be able to adjust the hole distribution in the paddle. Each disk has a different hole distribution. With the replaceable disk paddle the hole distribution could be changed easily as the conditions in the Rijke burner varied. While the small holes do not completely eliminate the unwanted oscillations, they have reduced them to an acceptable level.

Particle Feeder

One of the biggest problems encountered in the project was the development of a particle feeder which would feed small particles (5-50 micron) into the particle feeder at a controlled, measureable rate. The flow rate of the particles had to be fairly constant and in the range of 5 to 50

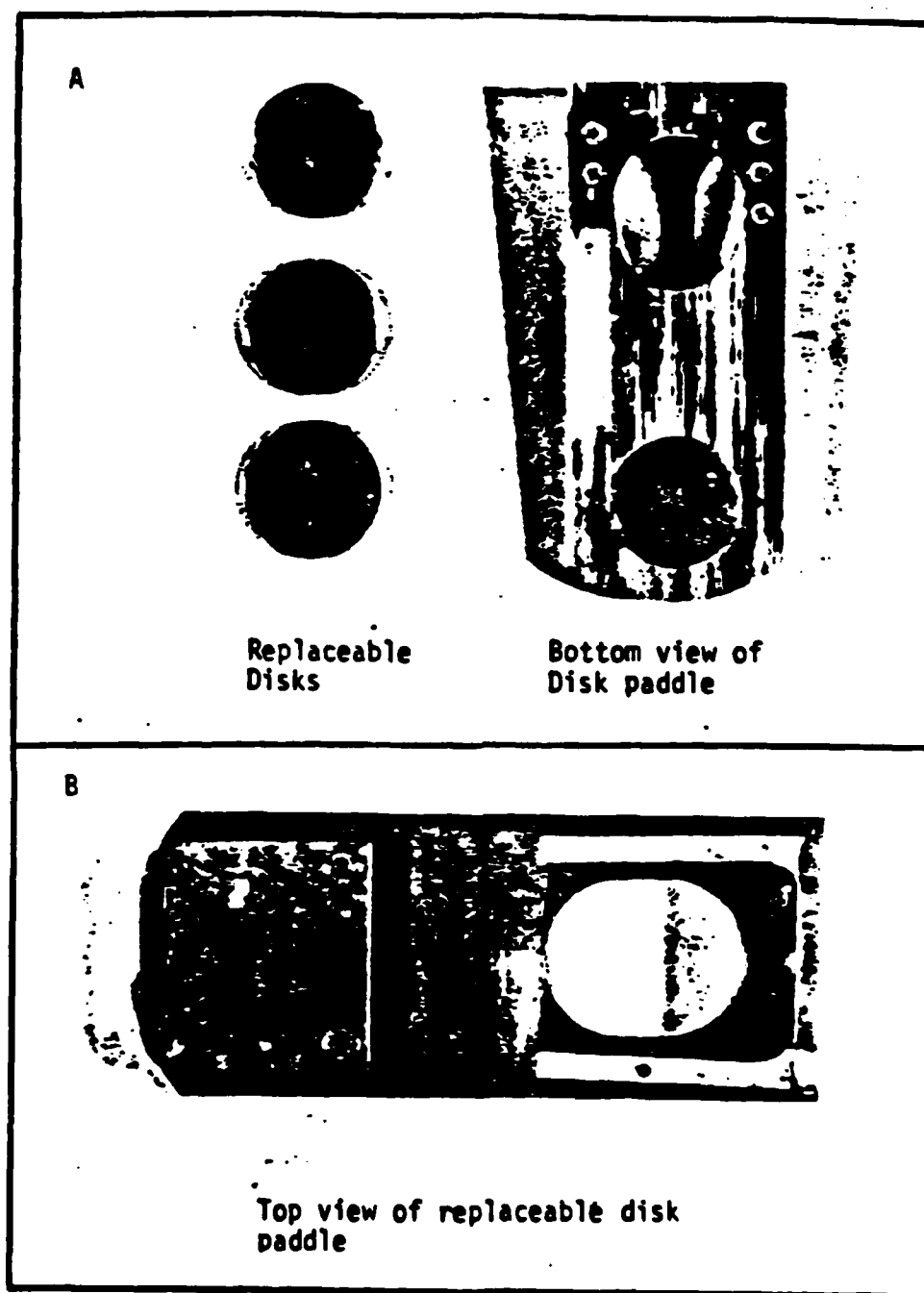


Figure 6. Replaceable disk paddle and three typical replacement disks used to suppress acoustic oscillations in the Rijke burner.

grams per hour. The problem of feeding particles at such a low flow rate and holding the flow rate constant was not easily overcome. Initially a screw type feeding system was investigated. A screw type feeder normally provides a constant stream of particles with the flow rate dependent upon the speed of the screw. The major problem encountered using the screw feeder was that the aluminum particles would pack together in the threads of the screw, preventing the screw from turning and stop the flow of particles. Attempts were made to prevent the screw from binding by providing more clearance for the threads, however when this was done the particle flow rate became very erratic.

The second type of particle feeder investigated was a fluidized bed. This seemed to work better than the screw feeder and an effort was made to improve the initial model. After considering several different modifications it was determined to use a particle feeder which had been developed by Hamor and Smith during the early 1970's (Hamor, 1971).

A schematic of the fluidized bed particle feeder is shown in Figure 7. The fluidized bed particle feeder was constructed, and after slight modification in the design of Hamor and Smith, the particle feeder functioned satisfactorily. In their design most of the gas goes out through the top after being filtered through a glass frit and only a small percentage goes out through the particle tube. While in our system all the incoming gas goes out the particle tube. This modification made it possible to run the particle feeder at a higher mass flow rate, produced a more constant particle flow rate and eliminated the problem of the glass frit filter becoming clogged with particles.

The particle feeder operates as follows. Particles are loaded into the particle feeder through the removable top and rest on the fritted glass disk near the bottom of the feeder. Nitrogen is fed into the particle feeder in

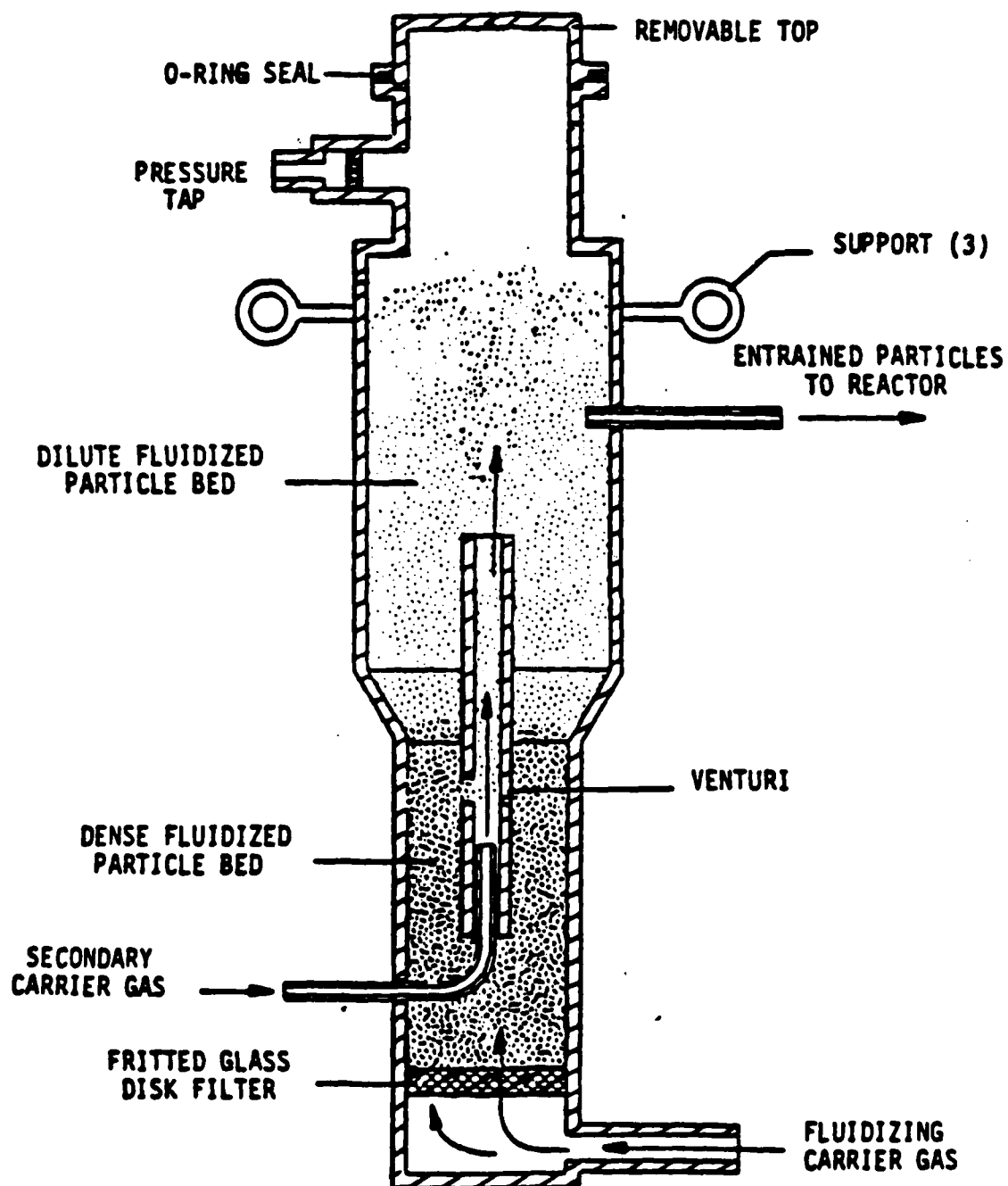


Figure 7. Schematic of fluidized bed particle feeder used to feed particles to the Rijke burner.

two streams, fluidizing and secondary. The fluidizing stream enters at the bottom of the feeder and passes through the bottom glass frit. This creates a dense fluidized bed in the bottom half of the particle feeder. The secondary stream enters through a small capillary tube (1 mm i.d.) and passes through a small venturi (2 mm i.d.) which rests on the intake capillary tube. Particles from the dense bed enter the venturi through a small hole and are entrained in the capillary tube by the secondary stream. They then move into the upper part of the feeder, forming the dilute fluidized particle bed. The actual particle flow rate is controlled by changing the total gas flow rate through the feeder and/or changing the size of stainless steel tube used.

The particle feeder is suspended from a precision balance and the flow rate of particles is determined by recording the voltage output from the balance on a strip chart recorder. The scale on the strip chart recorder is calibrated for each individual run by adding a known weight to the particle feeder and recording the response on the strip chart. The gas flow rates through the particle feeder are controlled using precision rotometers and needle valves.

Calibration

Many of the pieces of equipment in use in the experiment require calibration. The specific pieces of equipment which have been calibrated include the gas rotometers, chart speed on the visicorder, galvanometers, amplifiers and the transducer in use. Details of these calibration can be found in the M.S. thesis of Braithewaite (1984).

CHAPTER IV

RESULTS

The purpose of this work is to measure the the distributed combustion of additives commonly used as acoustic suppressants for solid propellants, and to use the results of these measurements to gain a greater understanding of the role of distributed combustion in solid propellant rocket motors. Three different additives were studied: aluminum oxide, which is basically inert, zirconium carbide, a slightly reactive particle, and aluminum which is very reactive. This chapter presents the results of tests using these three particles as well as results of other pertinent tests.

Burner Characterization

The major work of characterizing the burner has been completed previously (Gordon, 1984). This work included determining the frequency and oscillation limits in the burner as a function of upstream and downstream tube length; oxygen to fuel ratio; nitrogen flow; and the position of the velocity node relative to the flameholder. However two important burner characterization studies have been conducted as part of the current work.

The first of these studies was one in which the oxygen to fuel ratio was held constant at a predetermined value and the nitrogen to oxygen ratio was varied. The range of nitrogen to oxygen ratios studied, varied from a value of approximately 2.0 (the point at which flashback occurred) to a value of approximately 3.7 (the point at which the oscillations ceased). Acoustic growth rate data was taken at several points between these two extremes and analyzed to determine the most stable operating position, or the position at which the scatter in the acoustic growth rates was at its minimum. The results of this study are shown in Figure 8. The most stable operating regime

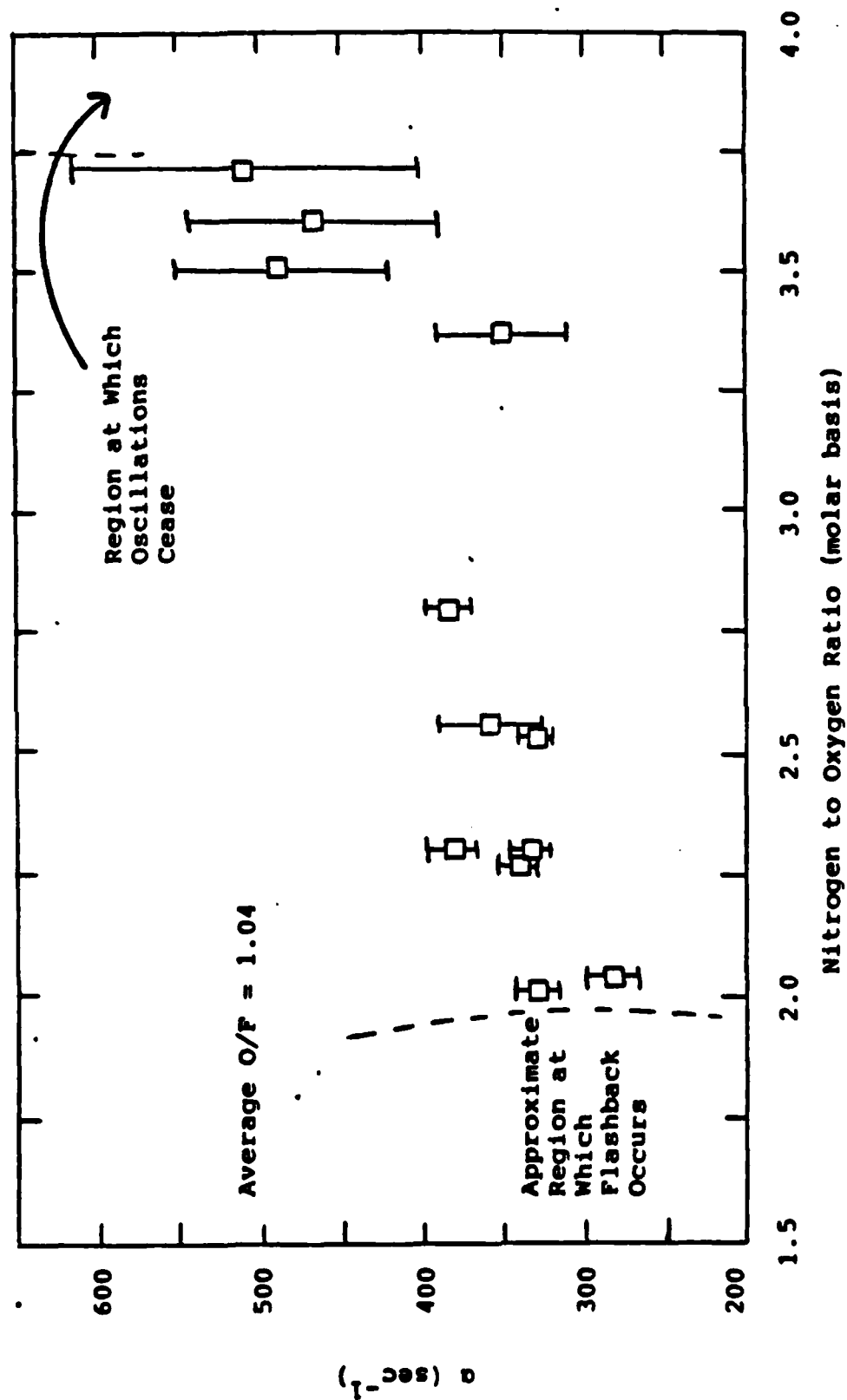


Figure 8. Acoustic growth rate (α) in the Rijke burner as a function of the nitrogen to oxygen ratio, error bars indicate one standard deviation from mean.

was found to be at a nitrogen to oxygen ratio of approximately 2.25 to 2.5 with the oxygen to fuel ratio fixed at approximately 1.0.

Another important study was conducted to learn if the acoustic growth rates were a function of time. To accomplish this the gas flow rates were held constant (along with all other variables) and data was taken at regular intervals for a period of approximately 20 minutes. The results of these tests are shown in Table 2. (Under normal operating conditions all data for a particular test run was taken within 10 minutes after ignition.)

Table 2
Acoustic Growth Rate Time Study

Time From Ignition (min)	Acoustic Growth Rate (sec. ⁻¹)
-----	-----
2.5	327
3.0	301
5.0	333
5.5	344
7.25	343
7.75	315
10.0	325
10.0	339
15.0	346
20.0	377

After analyzing this data it was determined that after a warm up period of two to three minutes, the growth rates did not depend on time for at least 15 minutes. This study was important because it showed that the burner reaches steady state quickly and will remain in that condition for an extended period of time.

Temperature Profiles

Temperature profiles for each of the particle types as well as for gas

only data were taken with 1/32" sheath diameter type K thermocouples (Chromel-Alumel). These profiles are shown in Figure 9. The equilibrium flame temperature is approximately 2500 K. It is apparent that the measured temperatures are very low, especially near the flame. One of the thermocouples was located in the water cooled section of the burner and as a result undoubtedly produced low temperature readings. However, it is also likely that the low temperatures measured by the other thermocouples are due in part to the radiation losses from the thermocouples. In the cases involving particles it is important to note that Smoot et al., (1978) found that deposition of solids on the thermocouple bead tends to augment the radiative loss, resulting in even lower temperatures. (For example: Mackowski et al. (1981) recorded temperatures in pulverized coal flames using both thermocouple and pyrometer measurements and in certain cases the thermocouple measurements were 700 K lower.) This would explain the reason that the temperatures recorded for the gas only case are initially higher than those cases involving particles. Because of the problems involved getting quantitative temperature data using thermocouples it would be prudent to use more sophisticated techniques to obtain temperature profiles in the future.

Despite the qualitative nature of the temperature profiles presented above, it is important to note that the temperatures in the Rijke burner are higher when aluminum and zirconium carbide are present than when aluminum oxide has been added to the system. This is likely a result of the energy added to the system when the aluminum or zirconium carbide particles burn. A second very important observation is that there are significant heat losses as the gases travel out of the Rijke burner. This indicates that the usual assumption that the temperature is constant throughout the length of the Rijke burner is not accurate.

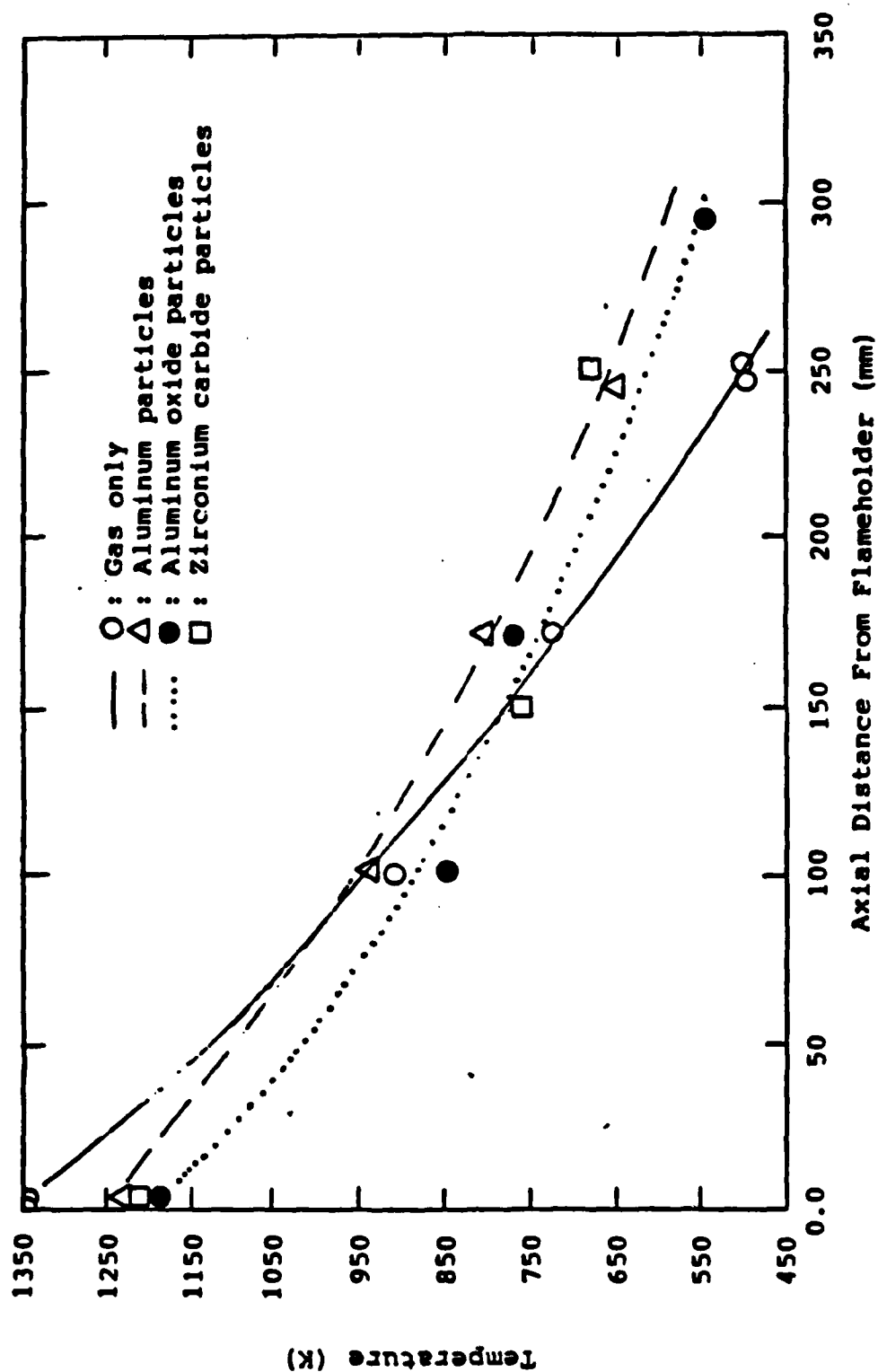


Figure 9. Temperature distribution in the Rijke burner with and without particle additives present.

Particle Size Analysis

Both pre and post combustion particle size analysis have been completed on each of the particles tested, i.e., 7 micron zirconium carbide, 10 micron aluminum oxide, and 13 micron aluminum. All particle size analysis was done using the Coulter Counter model TA II and standard coulter counter techniques (Owners Manual-COULTER COUNTER Model TA II, 1979). The results of these analyses are shown in Figures 10-12. The pre combustion particle samples were obtained by taking small random samples from the bulk material. The post combustion particle samples were obtained by one of two methods: first, by capturing the particles in a small cup as they came out of the Rijke burner and second, by removing particles from the sides of the quartz tube which had adhered to the tube after passing through the flame.

The particle size distributions obtained for particles before combustion should provide a good indication of the actual size distributions in the bulk particle samples. These distributions were used as the basis to determine the theoretical damping provided by each type of particle as discussed below. Unfortunately, the technique used to sample particles after they had passed through the burner was very qualitative in nature and probably does not provide an accurate picture of the post combustion particle size distribution. For example, many small particles (less than 2 micron) may have followed the gas flow which went around the collection cup instead of going into the cup as desired. This limits the validity of any analysis between pre and post combustion particle size distributions, hence the following comparisons must be taken in that light.

A comparison of the pre and post combustion samples revealed the following. As shown in Figure 10 the mass mean diameter of the 10 micron aluminum oxide increased after having passed through the burner. However, the

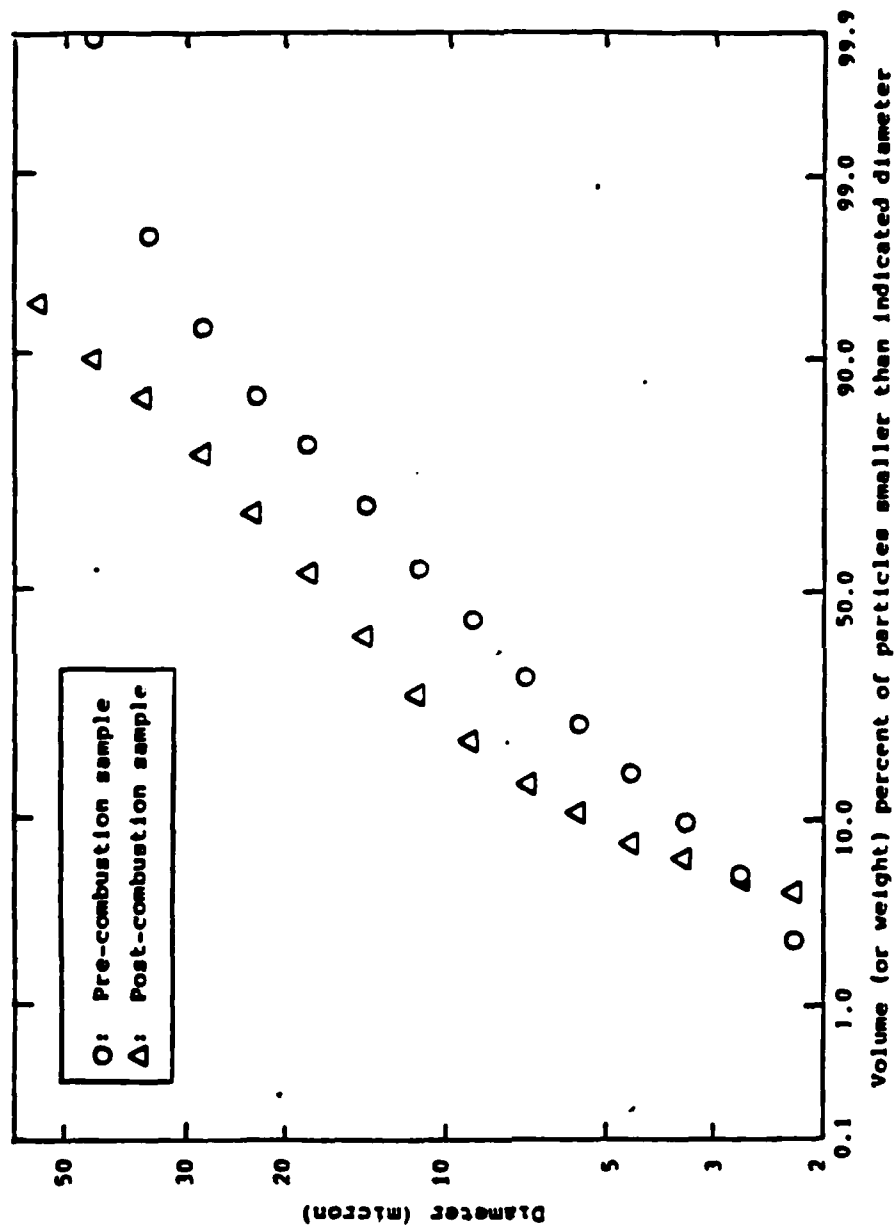


Figure 10. Particle size distribution by volume
(or weight) of 10 micron aluminum oxide.

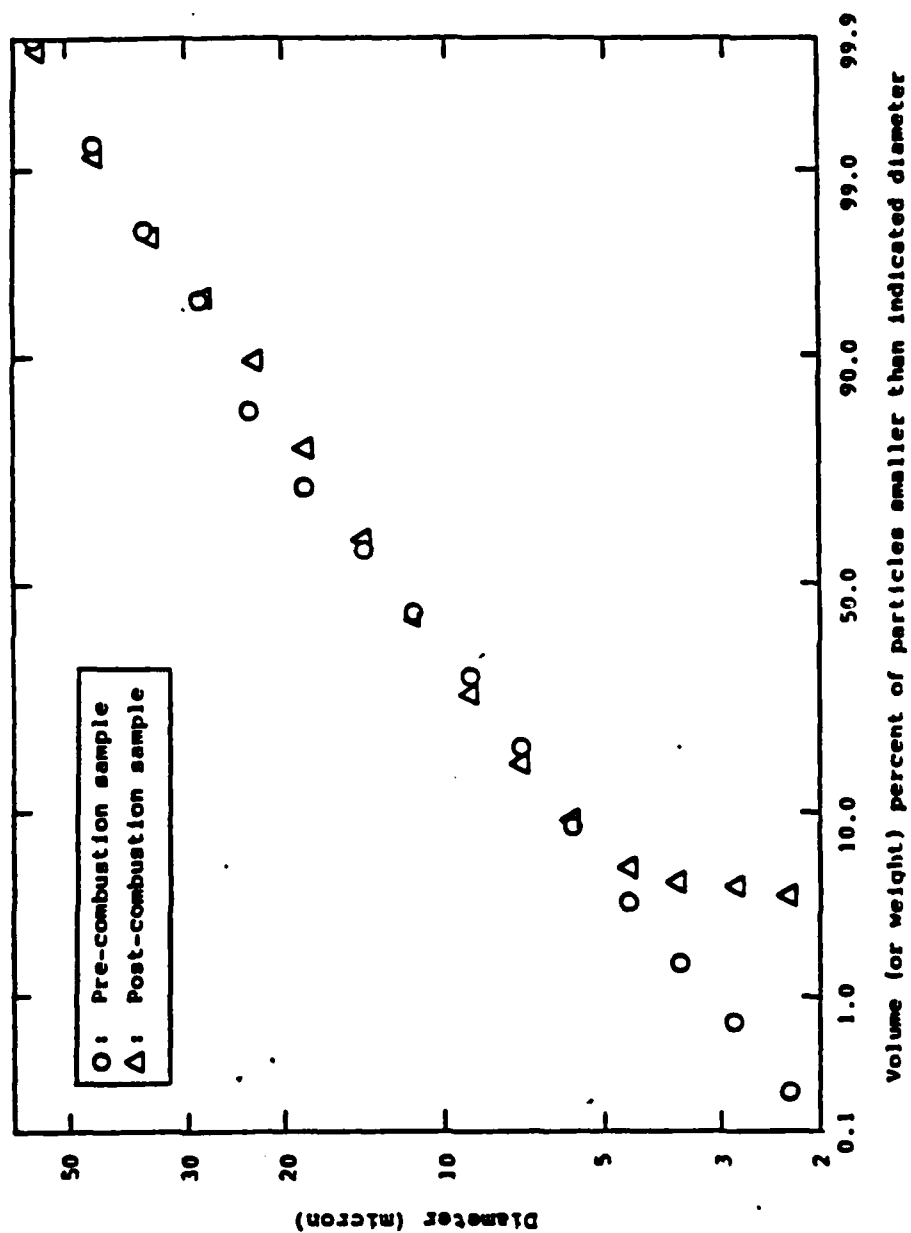


Figure 11. Particle size distribution by volume
(or weight) of 13 micron aluminum.

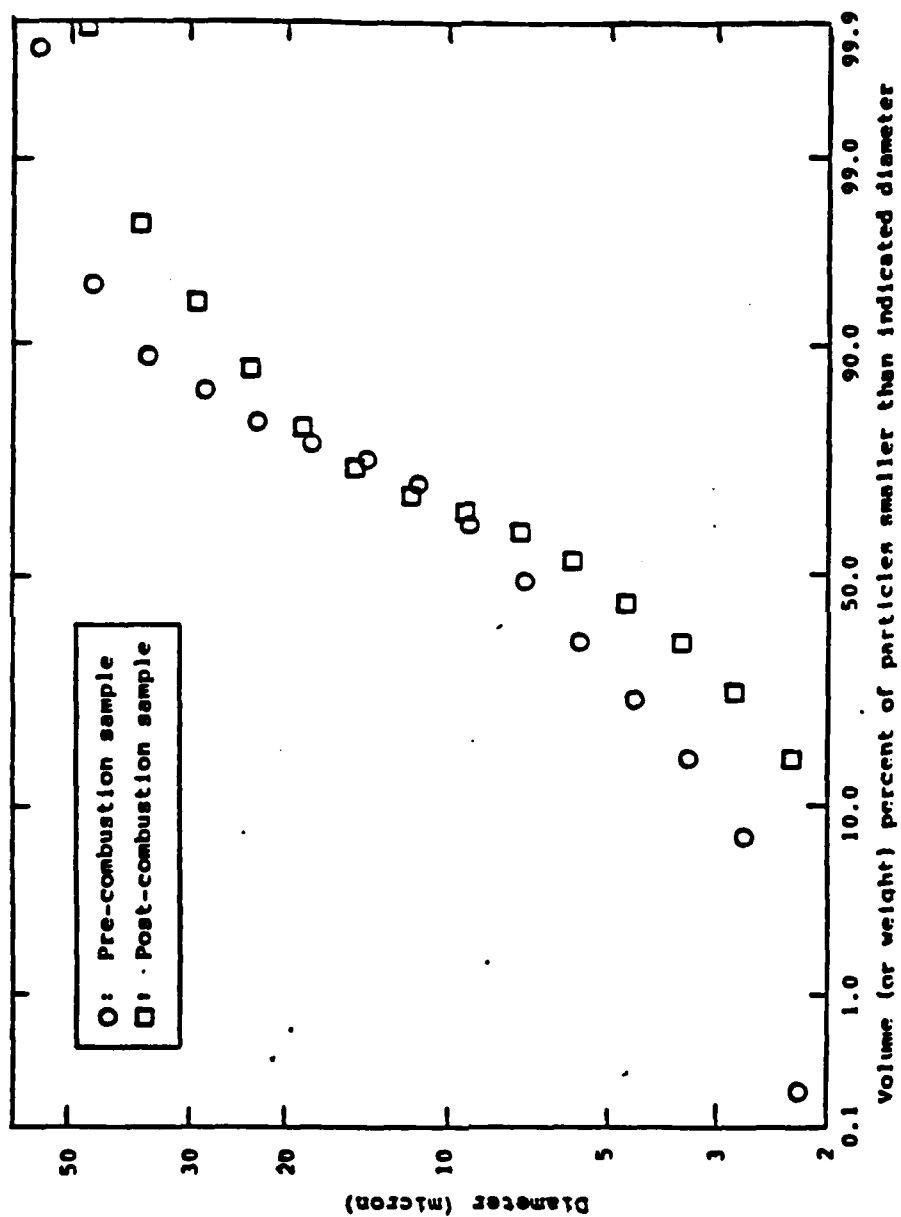


Figure 12. Particle size distribution by volume (or weight) of 7 micron zirconium carbide.

distribution was mono modal in both cases. Aluminum oxide is basically inert and was expected to pass through the burner without reacting. However, it is possible that the particles became hot enough to agglomerate as they passed through the flame which would explain the increase in the mass mean diameter. The post combustion size distribution of the 13 micron aluminum was very similar to the pre combustion size distribution, see Figure 11. The major difference occurred in the size range below 5 micron, in this range the post combustion sample contained a significantly greater number of particles. This could be the result of aluminum combustion to form aluminum oxide smoke. It also may indicate that only the particles smaller than 5 micron actually burn. As shown in Figure 12 the mass mean diameter of the zirconium carbide decreased after it had passed through the burner, also the distribution changed from a mono modal distribution to a bi modal distribution. It was expected that the particle distribution would change as the tube walls were streaked with zirconium oxide, indicating that some of the zirconium carbide had burned.

Particle Damping Calculations

Using the pre-combustion particle size data, particle damping calculations for each of the particles studied have been performed using Eq. 3. The results of these calculations are shown in Figure 13. The greatest amount of theoretical damping is provided by the 13 micron aluminum, followed by the 7 micron zirconium carbide, and the 10 micron aluminum oxide. However, the difference in the damping provided by the different particles is relatively small and becomes virtually negligible, when compared to the measured acoustic growth rates as discussed below. If the post-combustion particle size distributions were more reliable, they could be used to calculate the damping provided by the particles after they have passed through the flame.

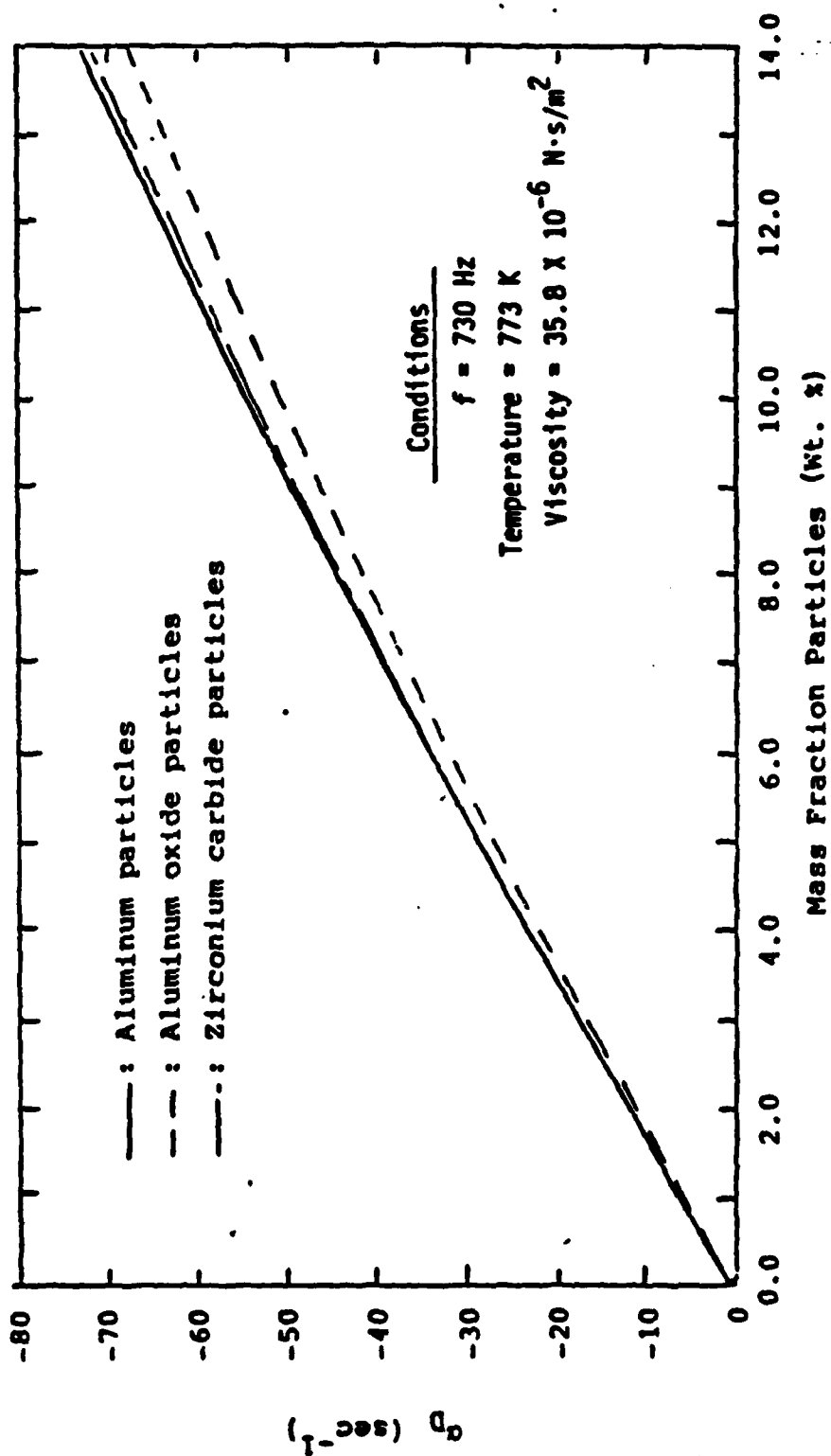


Figure 13. Theoretical damping provided by particles used as part of this thesis, calculated using Equation 5.

Because the theoretical damping is a strong function of particle diameter this information is needed to determine the damping which actually occurs.

Effects of Distributed Combustion

The process of distributed combustion in a rocket motor has generally been ignored in the past and the assumption made that all of the particle additive (usually aluminum) burns at the propellant surface (Culick, 1974). However, recent work by Beckstead et al. (1982) demonstrated that often a significant amount of aluminum burns and effects the acoustics environment after it has left the propellant surface. As the aluminum (or another reactive particle) burns, energy is added to the system and the particles themselves change in size. The changing particle size has a significant effect on the viscous particle damping and the distributed release of energy can either drive or dampen the acoustics of a rocket motor. In order to study the effects of distributed combustion in an acoustic environment several common acoustic suppressants were added to the Rijke burner in varying amounts. Acoustic growth rate and limiting pressure amplitude measurements were made for each test case and were used to evaluate the effect of distributed combustion and particle damping in the Rijke burner.

Inert Particles

Because aluminum oxide is a non-reactive particle no distributed combustion occurs and only particle damping and catalytic effects, if any, should be present. If the catalytic effects are small, when compared to particle damping, then the acoustic growth rates should decrease as more aluminum oxide is added to the system. A typical plot of pressure amplitude vs. time for a test using aluminum oxide is shown in Figure 14. Normally the acoustic growth rate would be determined by calculating the slope of the

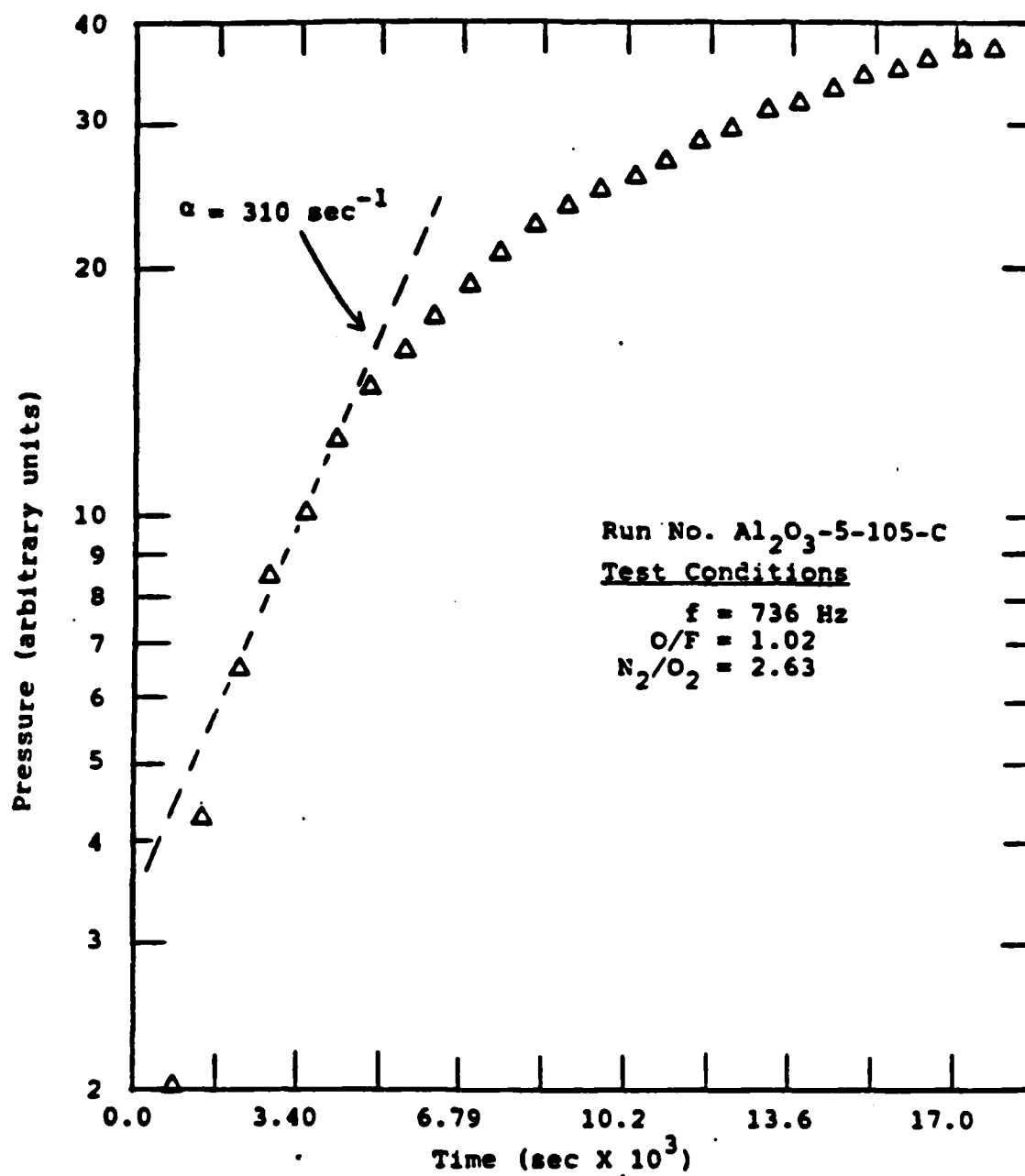


Figure 14. Growth of pressure oscillations in the Rijke burner with aluminum oxide particles present.

linear portion of such a curve using Eq. 2. For example, note the linear region shown in Figure 15 which is a pressure amplitude vs. time curve in the Rijke burner with no particles present. Unfortunately in the aluminum oxide case shown and virtually all other aluminum oxide test runs, no definitive linear region is present. This makes it difficult to determine an appropriate location on the growth curve to calculate the acoustic growth rate. As a result the growth rate data obtained using aluminum oxide is qualitative in nature. If the acoustic growth rates are calculated using the first few cycles of growth (this is normally the most linear portion of a growth curve) then the acoustic growth rates do not appear to change significantly as the aluminum oxide concentration is increased, as shown in Figure 16. The most likely reason the data shown in Figure 16 are so scattered is that the raw data is very non-linear as discussed above.

The limiting pressure amplitude data for the aluminum oxide test runs was significantly different from the data obtained using all other particles, in that it did not change as the mass fraction of aluminum oxide was increased (see Figure 17). In all other cases the limiting pressure amplitude decreased as the mass fraction of particles increased. This would tend to indicate that aluminum oxide has a catalytic influence on the gas flame. Perhaps this catalytic effect also influenced the acoustic growth rate and resulted in non-linear behavior.

Reactive and Slightly Reactive Particles

In addition to aluminum oxide two other types of particles were tested, aluminum and zirconium carbide. Both Al and ZrC are reactive particles. The reactions of Al and ZrC are shown below

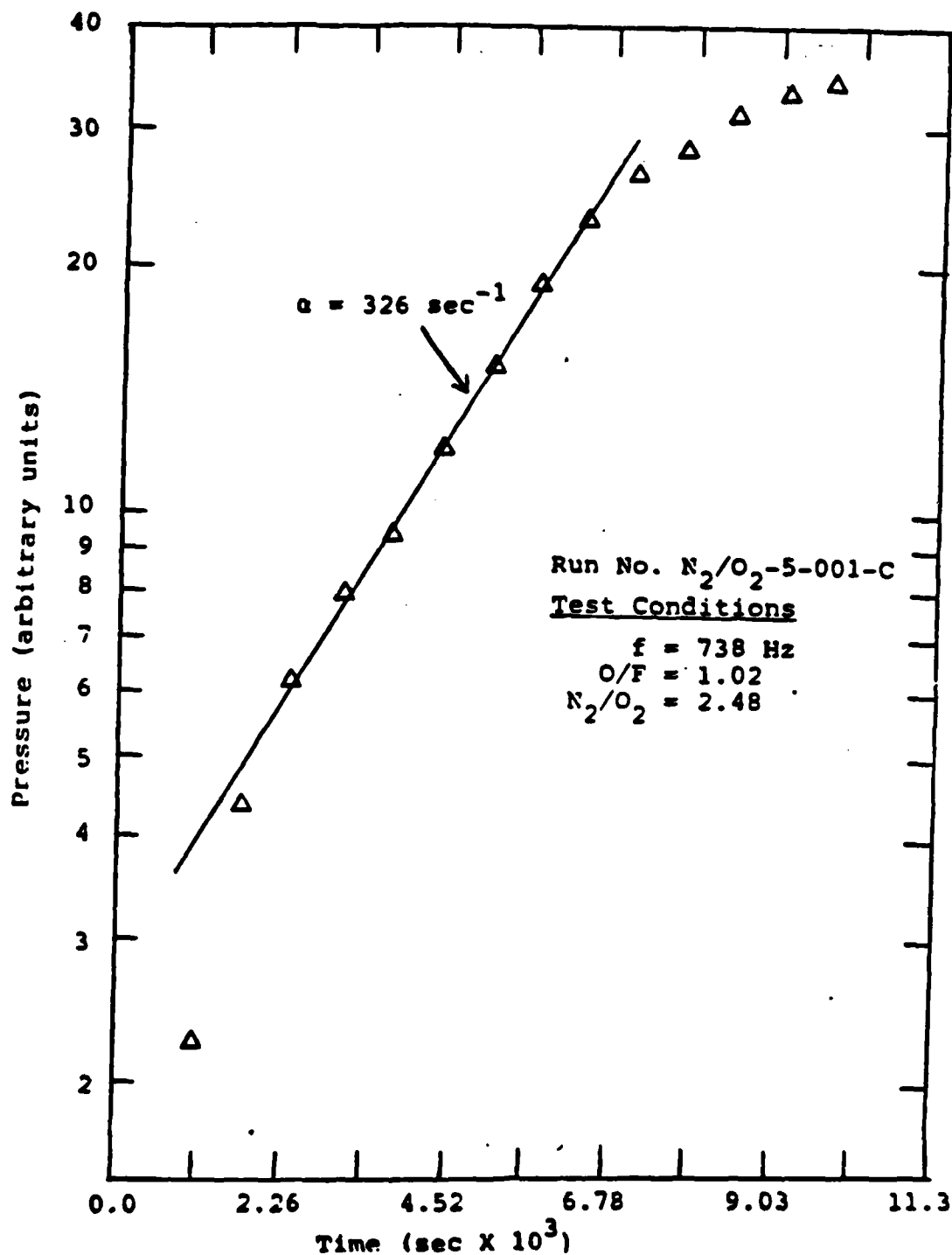


Figure 15. Growth of pressure oscillations in the Rijke burner with no particles present.

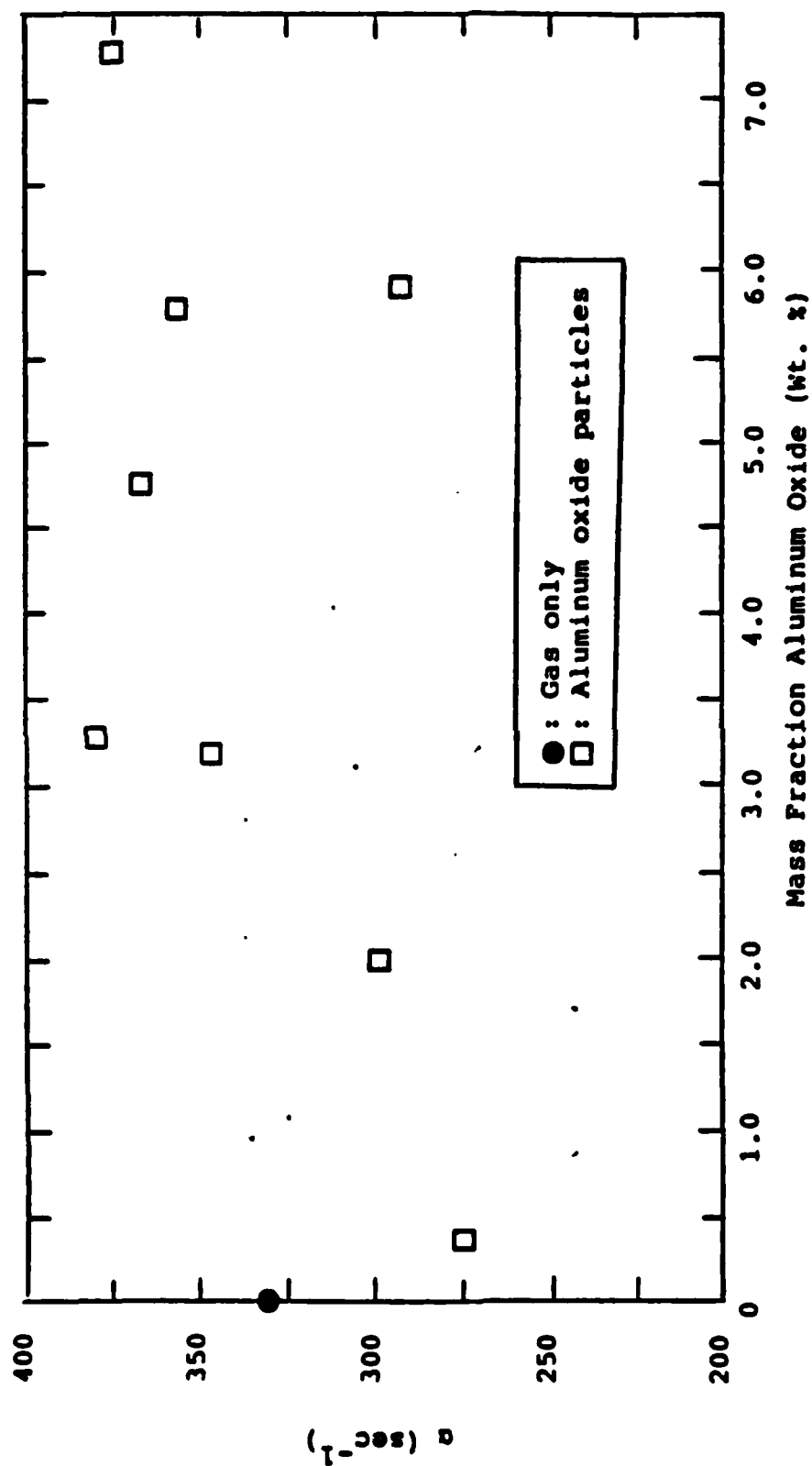


Figure 16. Acoustic growth rate (α), vs. mass fraction 10 micron aluminum oxide in the Rijke burner.

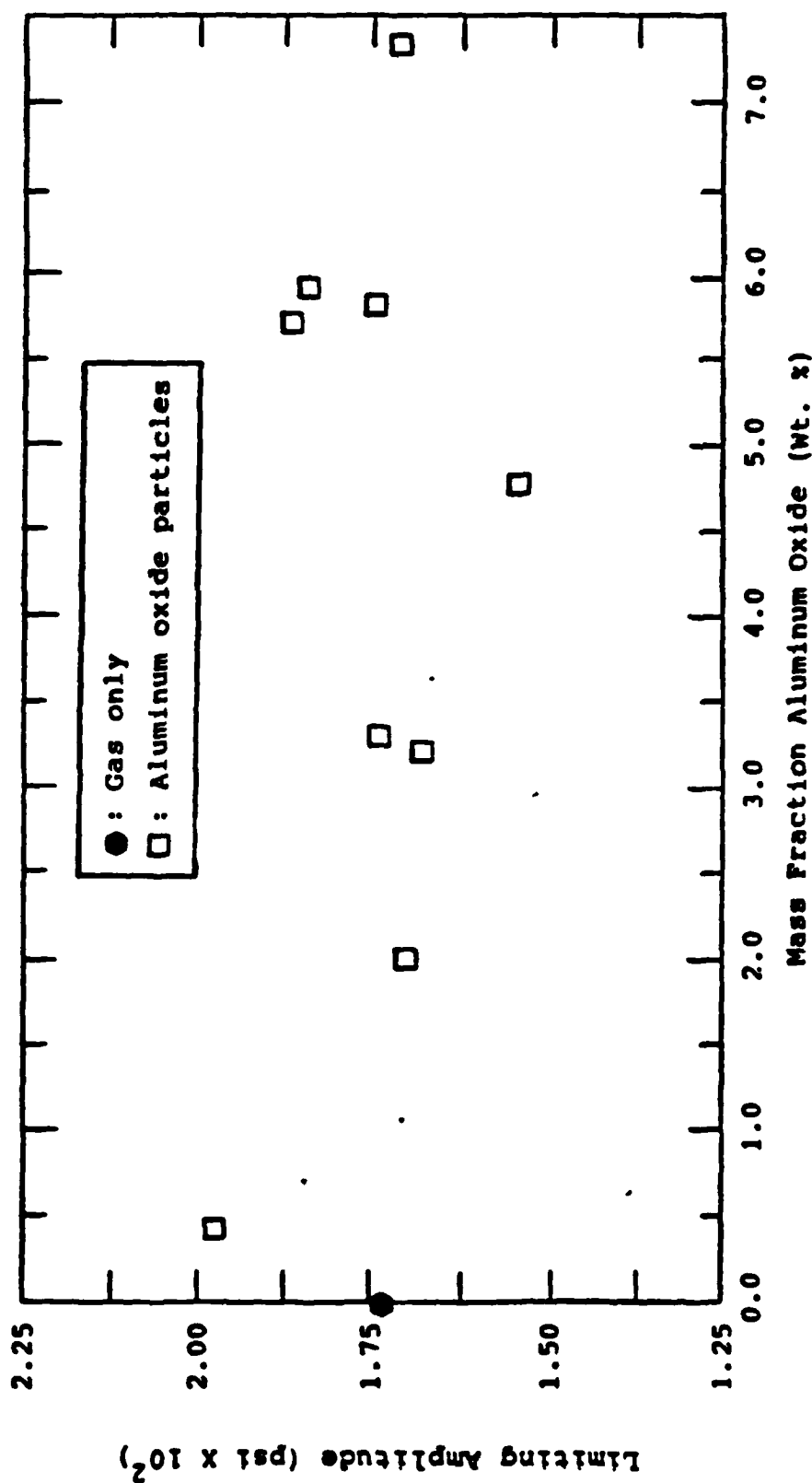


Figure 17.. Limiting pressure amplitude vs. mass fraction aluminum oxide in the Rijke burner.



On a weight basis the heats of reaction for Al and ZrC are -7.4 Kcal/gm Al and -3.1 Kcal/gm ZrC respectively.

It is probable that Al will react more readily than ZrC due to the fact that it has a lower melting and boiling point. Because Al is more reactive and its reaction will release more than twice the energy the reaction of ZrC does, Al would be expected to have a greater influence on the acoustics of the system than ZrC.

Both Al and ZrC were tested in the Rijke burner at several different mass loadings. The acoustic growth curves, for tests involving both particles, were much more linear than those obtained when aluminum oxide was added, as shown in Figures 18 and 19 (compare with Figure 14). This made it possible to determine the actual growth rates with a reasonable degree of certainty. The major difficulty in determining growth rates when Al or ZrC are added is that the oscillations grow so quickly that the number of data points which can be in the linear portion of the growth curve is limited. Both particle additives caused the acoustic growth rates to increase significantly over the baseline case with no particles present as shown in Figure 20. In both cases the acoustic growth rates increased as the mass loading increased, and as expected the growth rates for tests using Al were higher than those using ZrC.

Assuming that the increase in the acoustic growth rate is directly related to the heat of reaction, it should be possible to divide the acoustic growth rate due to distributed combustion by the appropriate heat of reaction and arrive at a new "pseudo" acoustic growth rate which should be independent of the heat of reaction. In order to calculate the acoustic growth rate due

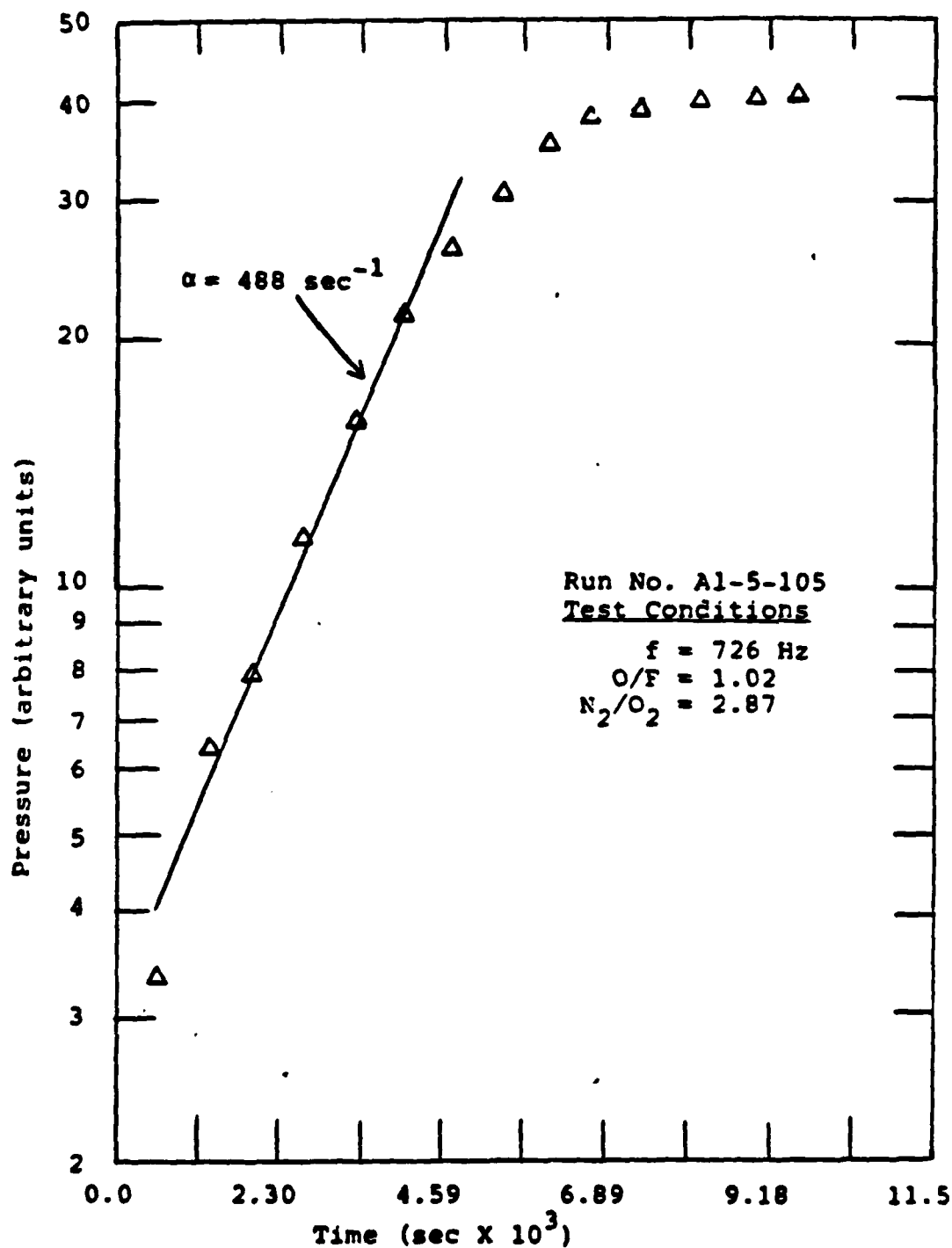


Figure 18. Growth of pressure oscillations in the Rijke burner with aluminum particles present.

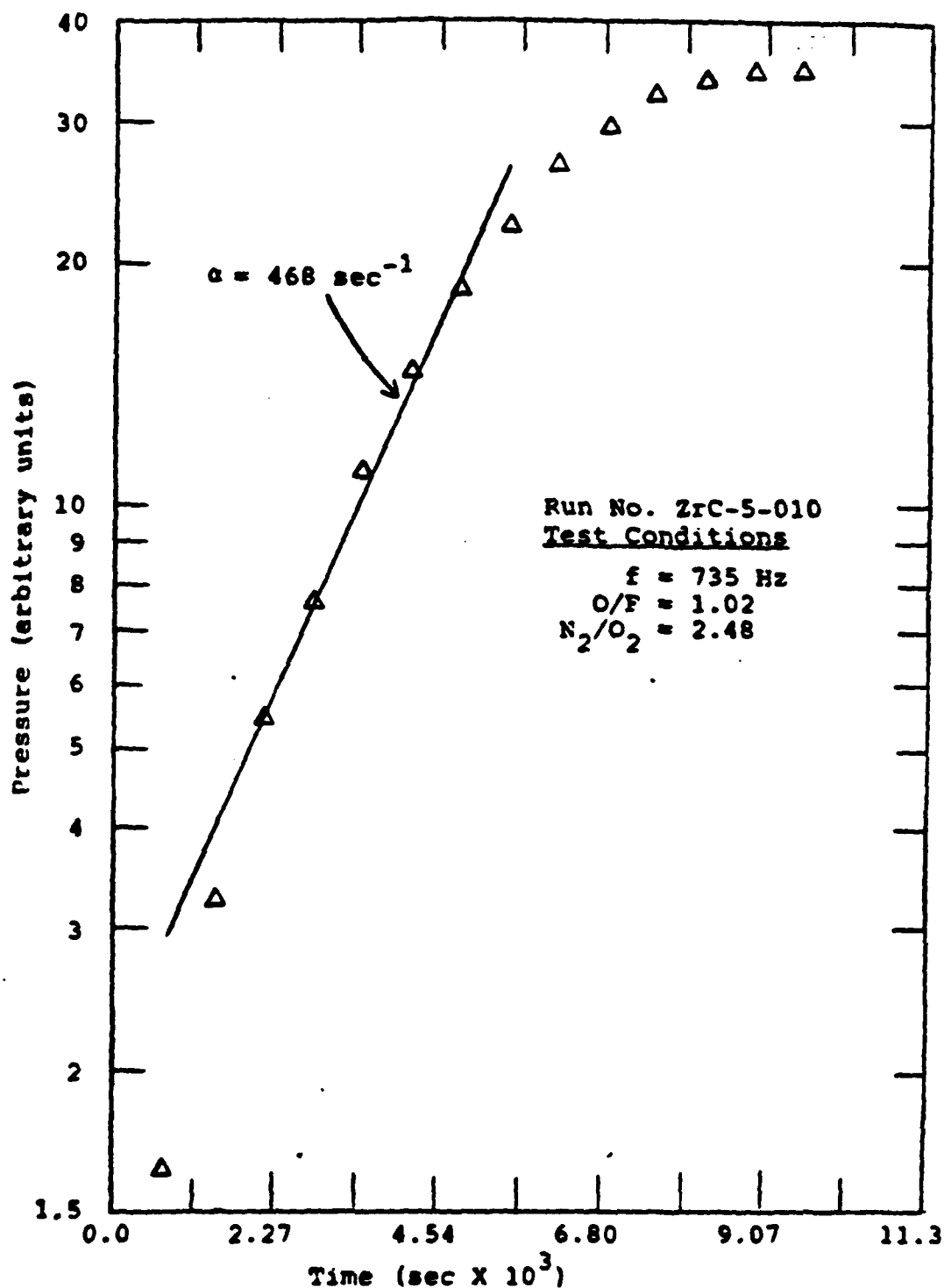


Figure 19. Growth of pressure oscillations in the Rijke Burner with zirconium carbide particles present.

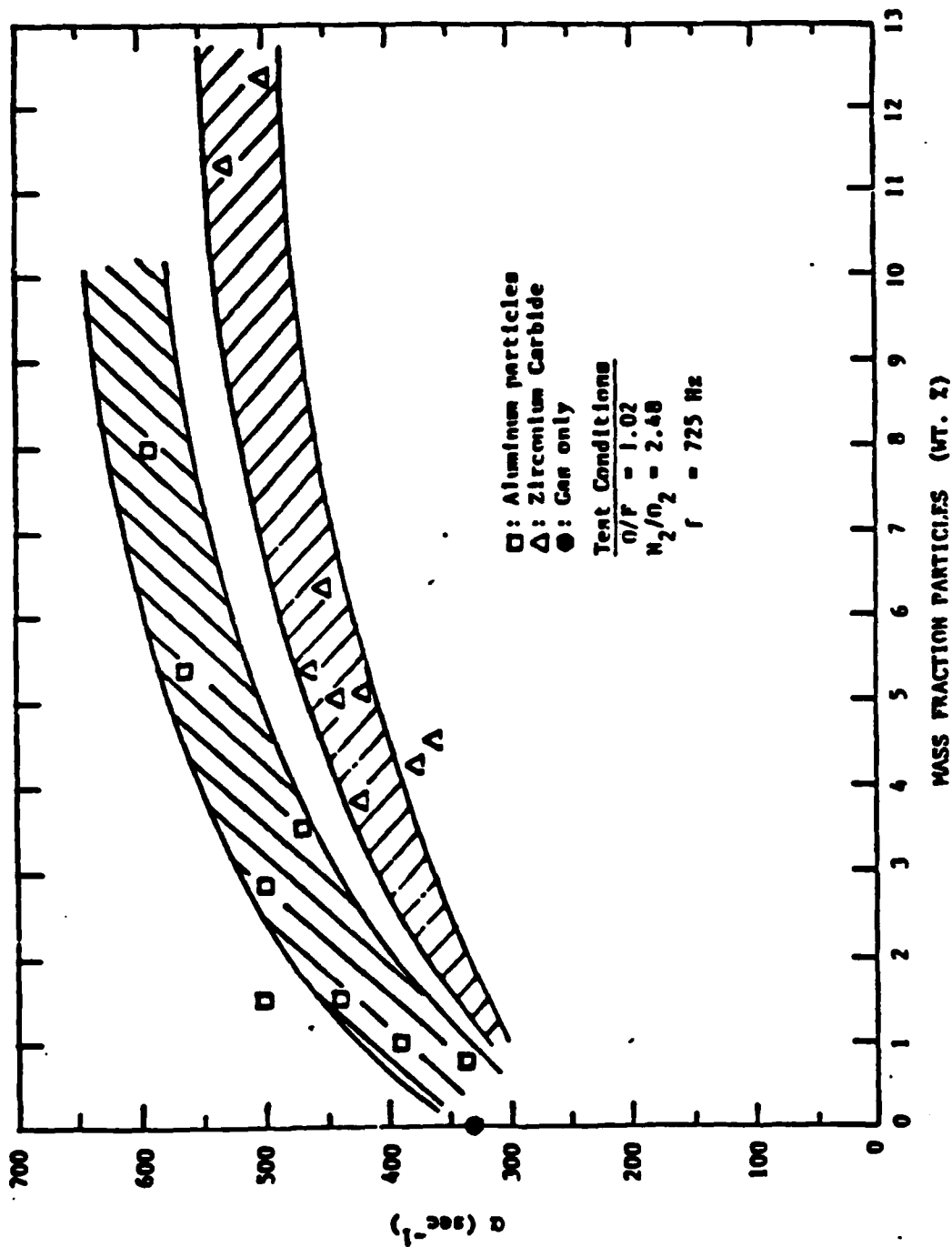


Figure 20. Acoustic growth rate (α) in the Rijke burner vs. mass fraction aluminum and zirconium carbide.

to distributed combustion the average acoustic growth rate (330 sec.^{-1}) of the baseline case was subtracted from the growth rates obtained with Al and ZrC present. (Note that this procedure neglects any catalytic effects due to the particles which may be present.) The results of these calculations are shown in Figure 21 for the 7 micron ZrC and 13 micron Al. While the "pseudo" growth rates for the ZrC appear slightly higher than those calculated for Al, when the original data scatter is considered the agreement is remarkable.

While the acoustic growth rates appear to be the primary function of distributed combustion, the limiting pressure amplitude is expected to be influenced primarily by non-linear damping within the system. While the damping provided by the 13 micron Al is different than that provided by the 7 micron ZrC (see Figure 13) the difference is very small when compared to the acoustic growth rates measured in the Rijke burner. As a result the limiting pressure amplitude for the two cases would be expected to be similar. For both types of particles the limiting amplitude decreased as the mass loading increased, and as expected the actual amplitude for the two cases for a given mass loadings was virtually the same (see Figure 22).

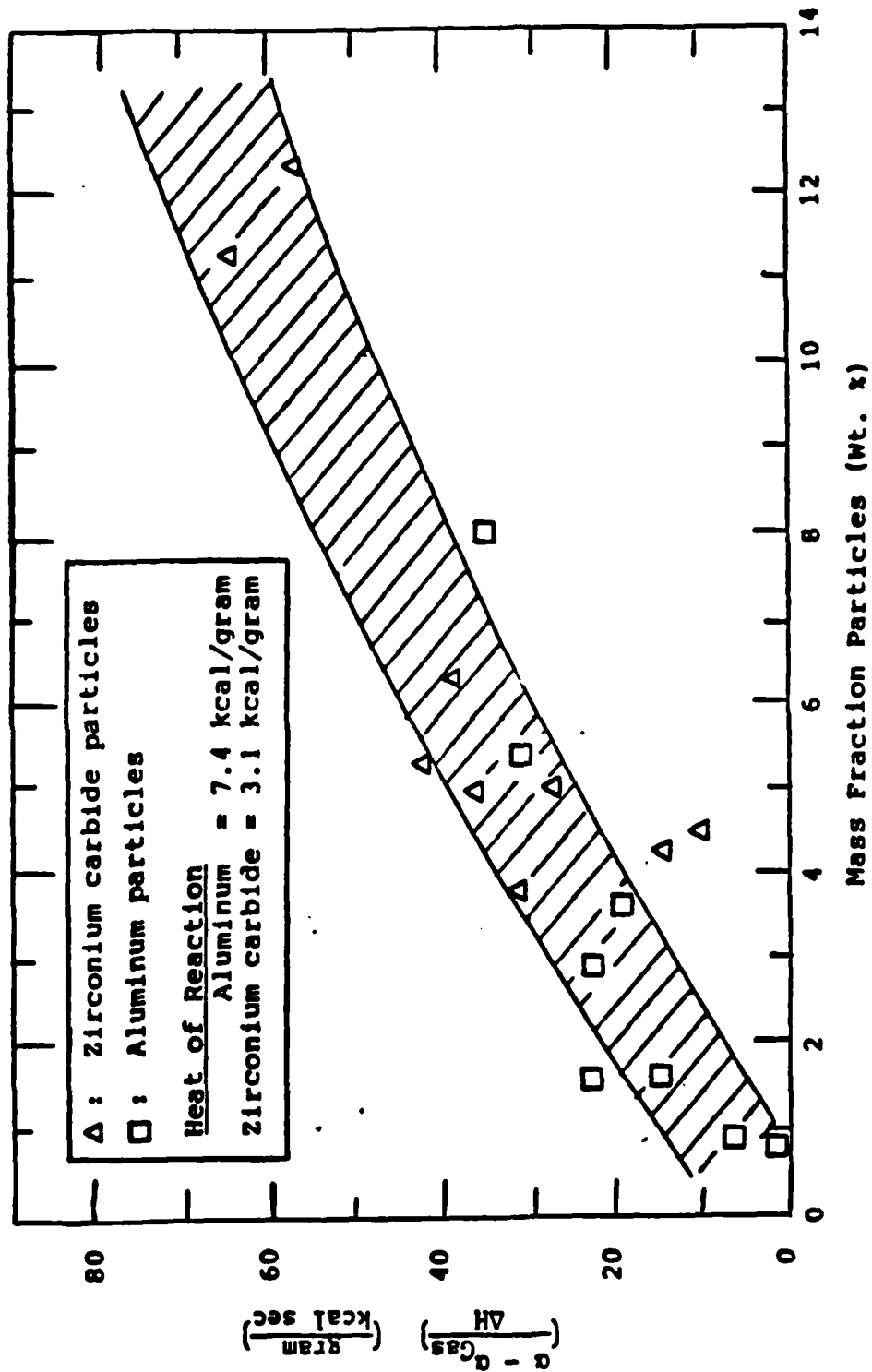


Figure 21. "pseudo" acoustic growth rate vs. mass fraction of 13 micron aluminum and 7 micron zirconium carbide (mass mean diameter).

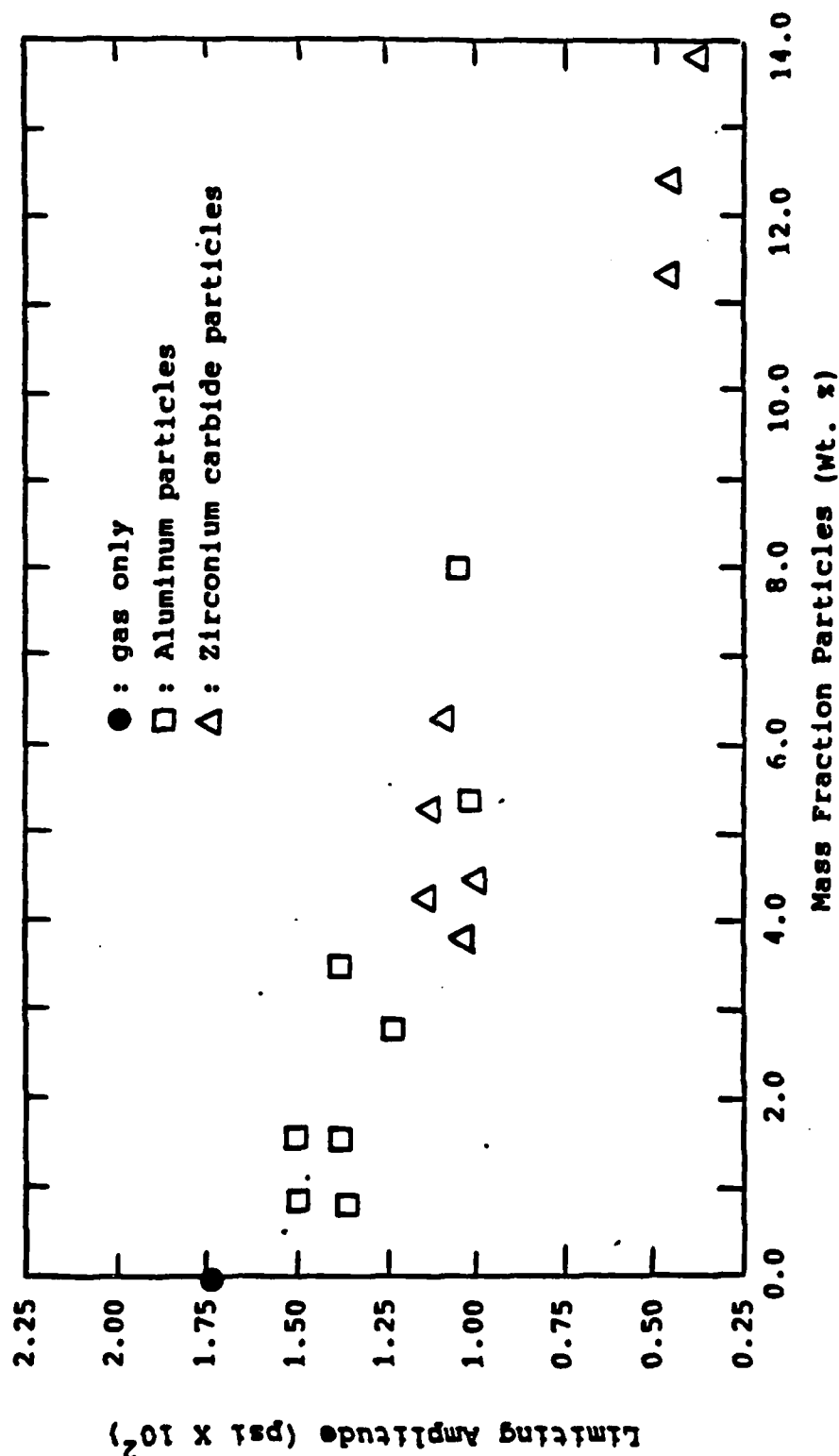


Figure 22. Limiting pressure amplitude vs. mass fraction aluminum and zirconium carbide in the Rijke burner.

CHAPTER V

CONCLUSIONS

An initial study of three acoustic suppressants commonly used in solid rocket propellants has been completed. This study was completed using the Rijke burner to create an acoustic environment which is similar to that found in a solid propellant rocket motor. Because the Rijke burner does not use solid propellant, it was possible to study the effect of distributed combustion of a given additive without the catalytic influence the additive would have on the propellant response function. It is believed that this work represents the first quantitative study of the mechanism of distributed combustion in an acoustic environment.

One conclusion may be drawn by studying Figures 16 and 20. Figure 16 shows the acoustic growth rate in the Rijke burner with aluminum oxide added. Figure 20 shows the acoustic growth rate as a function of mass fraction Al and ZrC. While the data represented in Figure 16 is not as reliable as that represented in Figure 20, it is clear that aluminum oxide does not cause the acoustic growth rate to increase in the same manner as Al or ZrC. (This conclusion may also be drawn by comparing the plots of pressure amplitude vs. time for each type of particle, eg. Figures 14, 15, 18, and 19.) The increase in the acoustic growth rate, in the case of Al and ZrC, is undoubtedly the result of energy being added to the system by the distributed combustion of the suppressant particles.

It also appears that the increase in the acoustic growth rate due to distributed combustion is directly related to the heat of reaction of a given particle, as shown in Figure 21. This being the case, the larger the heat of reaction a given acoustic suppressant has, the more significant effect it is likely to have on the acoustics of the system.

In addition to the information obtained regarding the mechanism of distributed combustion, additional understanding was gained about the operation of the Rijke burner. In particular, the most stable region of operation for the Rijke burner was determined for a particular set of flow conditions as shown in Figure 8. It was also determined that, after a short "warm up" period, the Rijke burner will operate at steady state for a relatively long period. The fact that the Rijke burner does have a stable region of operation, and that it will operate at steady state for an extended period of time are indications that it is a good experimental tool and may be used with confidence. It should be pointed out that the Rijke burner does operate at temperatures which are significantly lower than those found in solid propellant rocket motors. So that additives which do not burn in the Rijke burner may actually be reactive when used in solid rocket propellant.

The limiting pressure amplitude within the Rijke burner was found to decrease as the mass fraction aluminum or zirconium oxide increased, see Figure 22. This would seem to indicate that the limiting amplitude is influenced more by non-linear particle damping than by particle combustion. The addition of aluminum oxide did not influence the limiting pressure amplitude significantly, see Figure 17. It seems likely that the aluminum oxide actually catalyzes the flame and causes an increase in the pressure amplitude roughly equal to the decrease due to non-linear particle damping.

NOMENCLATURE

A	Arbitrary constant
a	Acoustical speed of sound
C_m	Mass fraction particulate matter in gas
D_i	Diameter of ith particle size
f	Average frequency
ΔH	Heat of reaction
l	Axial length
n	Integer
P'	Pressure fluctuation
P_0	Pressure amplitude, first cycle
P_n	Pressure amplitude, nth cycle
t	Time
t_n	Time interval between first and nth cycle
X_i	Mass fraction particles with diameter D_i

Greek Symbols

α	Acoustic growth constant or rate
α_{gas}	Acoustic growth constant for gas only
α_D	Acoustic or theoretical damping constant
μ	Gas viscosity or particle diameter in microns
ρ	Particle density
τ_i	Viscous relaxation time, $\frac{D_i^2 \rho}{18\mu}$, for particles with diameter D_i
ϕ	Phase angle
ω	Angular frequency

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